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MODIFICATION TO GOVERNMENT-OWNED THRUST STAND SYSTEM

CONTRACT NO. NAS 3-7925

by

J.D. SMITH

Prepared for

NATIONAL AERONAUTICS
AND
SPACE ADMINISTRATION

HUGHES

HUGHES AIRCRAFT COMPANY

RESEARCH LABORATORIES

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SUMMARY REPORT

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August 1966

CONTRACT NAS3-7925

Technical Management
NASA Lewis Research Center
Cleveland, Ohio

HUGHES RESEARCH LABORATORIES
A Division of Hughes Aircraft Company
Malibu, California

INTRODUCTION

The primary objective of Contract No. NAS 3-7925 was to extend the upper range of the NASA LeRC thrust stand system (previously developed under Contract No. NAS 3-5750) to 10 lbs. The necessary modifications were restricted to the electrical subsystems with no rework or dismantling of the mechanical portions of the system. Mechanical portions of the system are herein defined as those mechanical parts comprising the suspension and balance mechanisms. It was mutually agreed by NASA LeRC and HRL that the operating time of the thrust stand, responding to a force level of 10 lbs, would be dictated by the thermodynamic characteristics of the moving voice coil in the force motor. Preliminary estimates by HRL indicated the pulse duration should not last longer than 60 seconds for a steady 10 lb force level. This ultimately resulted in the prescribed 600 lbs-sec duty cycle for the system. Subsequent tests of the modified system have indicated that the original estimate was somewhat conservative and that a 1,000 lb-sec duty cycle will still provide a safe tolerance.

To attain the desired extension of the upper range of the thrust stand system to 10 lbs and to carry out other objectives in the modification, the following program was prescribed:

1. Provide a new power amplifier stage with a 60 watt, ±40 vdc, 1.5 ampere output capability.
2. Modify the voice coil load resistance network to facilitate the higher voltage and power levels.
3. Integrate the new electronic components with the existing control system and rework, rewire and retest to assure satisfactory operation over all thrust ranges.
4. Conduct a test program to determine permissible thrusting periods in the high thrust ranges and to specify minimum thermal recovery times.

5. Provide instrumentation to protect the force motor voice coil from thermal damage that might occur from excessive operation at the higher thrust level. Provide visual and/or audible warnings when maximum allowable temperature in the force motor is exceeded.

6. Amend the Instruction Manual - Thrust Stand System to include all modifications and new operating procedures as required. (See Appendix.)

7. Provide contractor field installation, cable harness modification, operational checkout and equipment calibration of the modified equipment at NASA LeRC and assure operation of the complete thrust stand system at the 10 lb force level.

All requirements and tasks set forth in Contract NAS 3-7925 have been met or surpassed. Modification, repair and installation of the government owned thrust stand was completed during the month of March 1966. The thrust stand components were shipped to NASA-LeRC on 18 March 1966 and arrived on 21 March 1966. HRL personnel arrived at NASA LeRC on 29 March 1966 to perform the equipment installation, operational check out and calibration. Field installation and check out of the thrust stand system was completed on 30 March 1966.

The modified Government Owned Thrust Stand System demonstrated a restoring force capability in excess of 10 lbs. The system was run closed loop with a static load of 12 lbs for several minutes to cause deliberate over heating of the voice coil and to demonstrate to LeRC personnel the over temperature alarm circuitry. As a result of the overload condition, audio and visual alarms were activated followed by automatic system shut down. The voice coil was then carefully inspected for damage. No damage was revealed. The automatic system shutdown feature provides the necessary added protection in the event the audio and visual over-temperature alarms are not seen or heard by the operator.

THRUST STAND MODIFICATION

Power Amplifier Stage

The modified system includes a modification to the power amplifier stage driving the voice coil. A Burr-Brown Model 9773, ±40 vdc, 1.5 ampere (60 watt) Power Amplifier was substituted for the original Burr-Brown, ± 10 vdc, 0.75 ampere (7.5 watt) Power Amplifier. The new power amplifier stage provides the added driving power to the force motor necessary to attain the 10 lb restoring force capability. With the new PA stage, the modified system has demonstrated a restoring force in excess of 12 lbs.

The power amplifier is provided with a zero adjustment to null the output when the input is zero. This adjustment is on the top side of the chassis. Details of this adjustment are provided in the Burr-Brown, Model 9773, Power Amplifier Instruction Manual. The PA is further provided with a front panel vernier gain adjustment. The range of this adjustment is from 1 to 11, thus providing the operator with a manual control of the system closed loop gain.

Power Distributor Chassis

The Power Distributor Chassis provides line regulation of the 117 vac, 60 cps line voltage. In addition, the system modification included the addition of a +28 vdc, 7.0 ampere supply to this chassis. This results in the NASA LeRC Thrust Stand System having a self contained +28 vdc supply in the control console. No external +28 vdc source is required.

Force Motor Over-Temperature Alarm Circuits

Force motor over-temperature alarm circuits have been fabricated and modularized such that the new unit plugs directly into the obsolete power amplifier slot in the Platform Control Network. This unit is designed to activate an audio alarm (horn) and a visual warning (Force Motor Over-Temp Alarm) on the Indicator Panel when the voice coil resistance has increased to 30 ohms (due to over temperature) from the nominal coil resistance of 18 ohms and to automatically return the system to the "STANDBY MODE" of operation when the coil resistance rises to 32 ohms. In order to return the system to the "OPERATE MODE" the operator must press the OPERATE switch. The over-temperature alarms will activate any time the voice coil resistance is above 30 ohms.

The following list summarizes the engineering and technical efforts performed by the Contractor during this contract. The work performed is itemized by system unit.

1. Chassis - Power Distributor
   a. Modified to include +28 vdc power supply as well as voltage regulation of the 117 vac, 60 cps line voltage.
   b. Performed operational check out.
   c. Revised schematic diagram.
2. Control Network - Platform
   a. Replaced and rewired damaged Winchester Connector (MRA 41 P).
   b. Replaced damaged top cover.
   c. Modified voice coil loading resistor network (R_1, R_5, R_6, R_7) to accommodate increased driving power from new 60 watt power amplifier.
   d. Modified control network to include voice coil over temperature alarm signal circuit and over temperature shut down signal circuit.
   e. Replaced R_1 trimming pot with 10 Ω trimpot.
   f. Performed operational check out.
   g. Revised schematic diagram.
3. D. C. Power Amplifier (± 40 vdc, 1.5 amps)
   a. Replaced Burr-Brown, Model 1633, 7.5 watt power amplifier with Burr-Brown, Model 9773, 60 watt power amplifier.
   b. Performed operational check out.
   c. Revised schematic diagram.

4. Panel-Mode Selector
   a. Modified electrical wiring to "Standby" relay to accommodate automatic system shut down in the event of severe voice coil over temperature.
   b. Changed Thrust-Impulse Range indicator decal to include a 10 lb range.
   c. Performed operational check out.
   d. Revised schematic diagram.

5. Indicator Chassis - Transducer Amplifier
   a. Replaced damaged Sanborn Displacement Transducer Indicator meter.
   b. Performed operational check out.

6. Burr-Brown ± 15 VDC power supply and operational amplifiers
   a. Complete factory check out and calibration to factory specifications.

7. Network Control Panel (Back of Chassis)
   a. Rewired obsolete power amplifier module slot to accommodate new Over-Temperature Alarm Network.
   b. Performed operational check out.
   c. Revised schematic diagram.

8. Panel-Indicator
   a. Modified Indicator Panel to include Force Motor Over-Temperature Visual Warning.
   b. Changed indicator decal.
   c. Performed operational check out.
   d. Revised schematic diagram.

9. Thrust-Impulse Network Modules
   a. Performed operational check out
   b. Prepared new schematic diagram.

10. Force Motor Over-Temperature Alarm Circuit
    a. Designed and fabricated new over-temperature alarm circuit.
    b. Installed new circuit in obsolete power amplifier module slot.
    c. Performed operational check out.
    d. Prepared new schematic diagram.

11. Installed audio alarm connected to voice coil over temperature alarm circuit in parallel with visual warning indicator.

12. Repotted and temperature cured voice coil with "Cycle Weld" to increase structural rigidity.

13. Modified console cable harness to accommodate thrust stand modification.

14. Audio Alarm (Horn)
    a. Installed voice coil over temperature audio alarm.
    b. Performed operational check out.

15. Performed electrical calibration, mechanical alignment and operational check out of the closed loop control system. Demonstrated system capability of measuring thrust levels in excess of 10 lbs. Tested alarm circuit with 12 lb static load.

16. Updated cable harness - wiring list.

17. Updated Instruction Manual - Thrust Stand System.

18. Modified cable harness to facilitate overload alarm.

SYSTEM OPERATION

The modification to the electronic circuitry to extend the upper range of the system to 10 lbs requires <u>no change</u> in the basic system operating procedure. Simple changes in the text of the Instruction Manual - Thrust Stand System, have been prescribed in the Errata Sheet accompanying the modified electrical schematics and wiring lists.

When operating in the 10 lb thrust range, a thrust force of 10 lbs is read out on the Digital Voltmeter as 1.000 volts. 12 lbs of force is read out on the 10 lb range as 1.200 volts. Thus, some over range can be tolerated on the upper thrust range.

To provide 10 lb of restoring force, the Power Amplifier is required to deliver approximately one amp of current to the force motor. The near linear relationship of voice coil current and restoring force allows measurement of the voice coil current (I_c) to be used as a measurement of the restoring force (F_r). Approximately one amp of current through the nominal 18 ohm voice coil and 1 ohm series resistor results in approximately 10 lb of restoring force. Thus, 1.0 amp of current results in a 1.000 volt drop across the series 1 ohm resistor and is read out on the Digital Voltmeter as 10 lb of thrust. The total series resistance of the voice coil (R_c), 1.0 ohm resistor (R_p) and line resistance (R_l) is a nominal 20 ohms. This results in an initial power amplifier (Ampl. 2) output of approximately 20 vdc to provide a 10.0 lb restoring force. When balancing a steady 10 lb force level, the voice coil dissipates 18 watts of power initially ($I_c^2 R_c$ = 18 watts). As power is dissipated in the voice coil, the temperature rise causes the coil resistance to increase. When the coil resistance has increased to 170% of the initial value (30 ohms), audio and visual alarms are activated causing a horn to sound and an over-temperature indicator to light on the Indicator Panel. If this warning is overlooked or ignored by the operator, an automatic system shut-down circuit is activated, when the voice coil resistance has increased to 180% of the initial value (32 ohms), to automatically place the system in the "STANDBY MODE". To return the system to the operating mode, the operator must press the "OPERATE" switch. If the voice coil resistance is still above 30 ohms the audio and visual alarm will again sound. If the voice coil resistance is above 32 ohms, the system will automatically return to Standby. Once the automatic shut down circuit has been activated, high thrust level measurements (approx. 10 lb) should be discontinued for approximately 1/2 hour. It is the operator's option whether he chooses to leave the system in the "STANDBY MODE" or in the "OPERATE MODE" with no load while allowing the voice coil to cool.

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APPENDIX

INSTRUCTION MANUAL - THRUST STAND SYSTEM

prepared by

A. J. Couvillion, J. D. Smith, and R. Kuberek

under Contract NAS 3-5750

(September 1964)

TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

FOREWORD

The thrust measuring system presented in this report is in response to NASA request number STD-189 dated 20 December 1963. A subsequent contract NAS 3-5750 dated 10 April 1964 provides for the development, test, and installation of the equipment.

The primary design features of the equipment are fast response and isolation from background vibration.

I. INTRODUCTION

The Hughes Research Laboratories Thrust Stand System, Fig. 1, combines an advanced electronic control system with a virtually frictionless high precision balanced platform. The system provides the measurement of thrust (in pounds) from 10 mlb to 5 lb in four range settings with a threshold of better than 1 % of any range setting. In addition, the system will measure impulse (in pounds second) from 10 mlb sec to 10 lb sec with a threshold of better than 1% of the range setting.

The HRL Thrust Stand fulfills the contract requirement for a high speed, dynamically stable system. The range of this equipment can be extended to micropound and 100 lb thrust scales, which has dictated such features as remote control, operations counter, automatic hold, self-contained static and dynamic calibrate, and multiple system operational modes.

The thrust stand system will demonstrate an approximate 100 cps frequency response with a 5 lb mass load. The Displacement Transducer Amplifier Indicator, which is a major part of the high speed control loop, provides full scale sensitivity of 3.0 V dc at 15 μin. The transducer amplifier thus provides 2×10^5 V/in. sensitivity to the over-all control loop gain.

The control console provides seven modes of operation with 24 sets of instrumentation indicators. Four ranges of thrust and impulse are available with the Thrust/Impulse Range Selector. These ranges are 0.01, 0.1, 1.0 and 5.0. Readout is provided by a four-place digital voltmeter and a two-channel strip chart recorder.

The balanced pendulum platform system is suspended on six sets of precision knife edges and bearing blocks. The bearing blocks are fabricated from M-2 tool steel and heat treated to R_c 64 with critical dimensions held to within ± 0.000025 in. Knife edges are fabricated from 440 C stainless steel and heat treated to R_c 60 with the critical dimension

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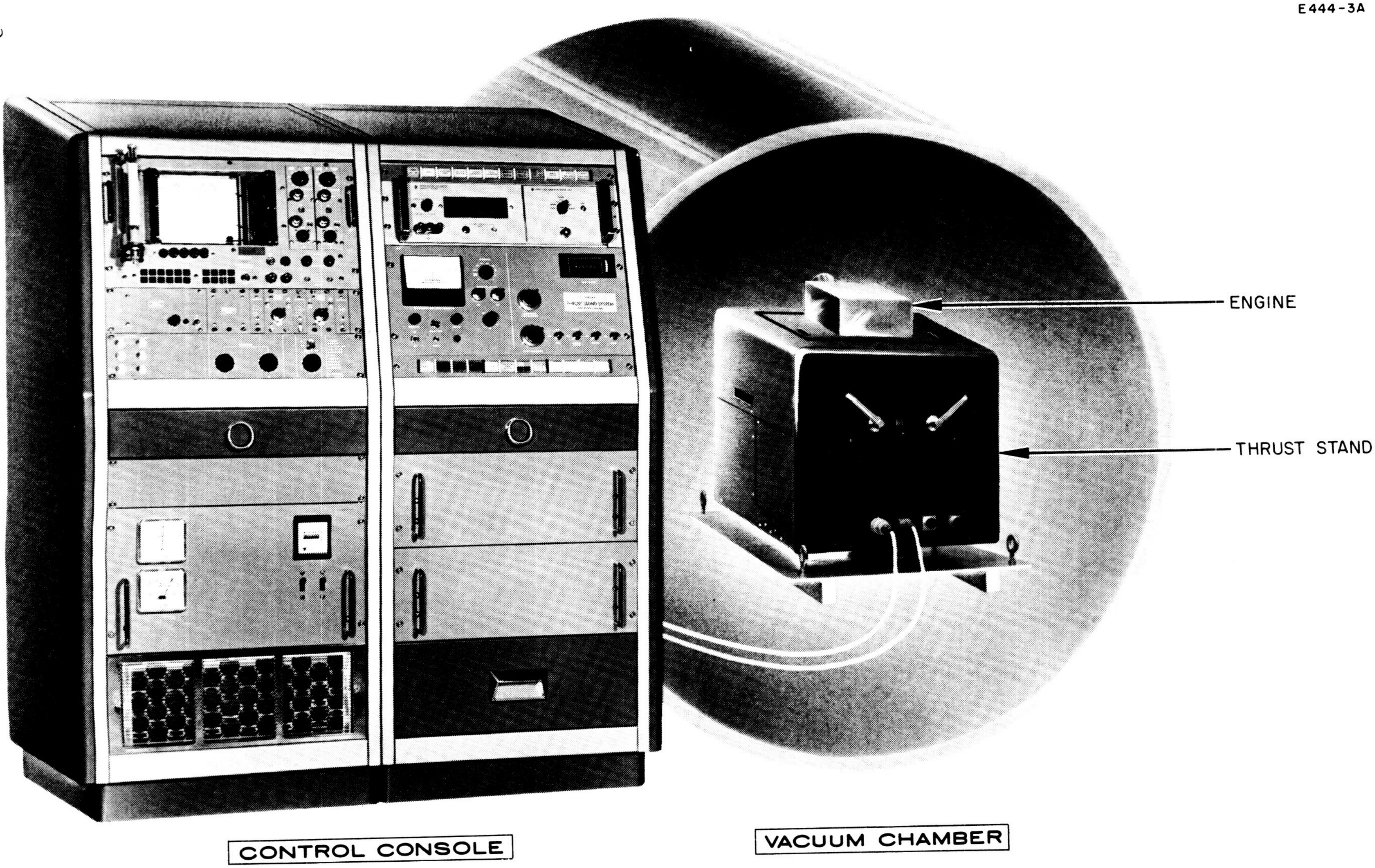

(a) Control system.

(b) Platform.

Fig. 1. The Hughes Research Laboratories Thrust Stand System.

also held to ± 0.000025 in. Surface finish on the bearing blocks and knife edges is to 4 μ in. The six knife edges and bearing block sets are aligned on their mountings to within 25 μ in. of their common reference.

Front and back views of the thrust stand (without cover) are shown in Figs. 2 and 3, respectively. Parts of the apparatus, as indicated in the figure, are listed below:

1. Counter weights (three)
2. Knife-edge and yoke (three)
3. Engine mounting platform
4. Static calibrator
5. Magnet
6. Voice coil
7. Level adjustment
8. Displacement transducer
9. Platform cage handles (two)
10. Platform instrumentation connector
11. Transducer connector
12. Engine system connector
13. Engine power connector
14. Dynamic calibrator
15. Platform vibrator

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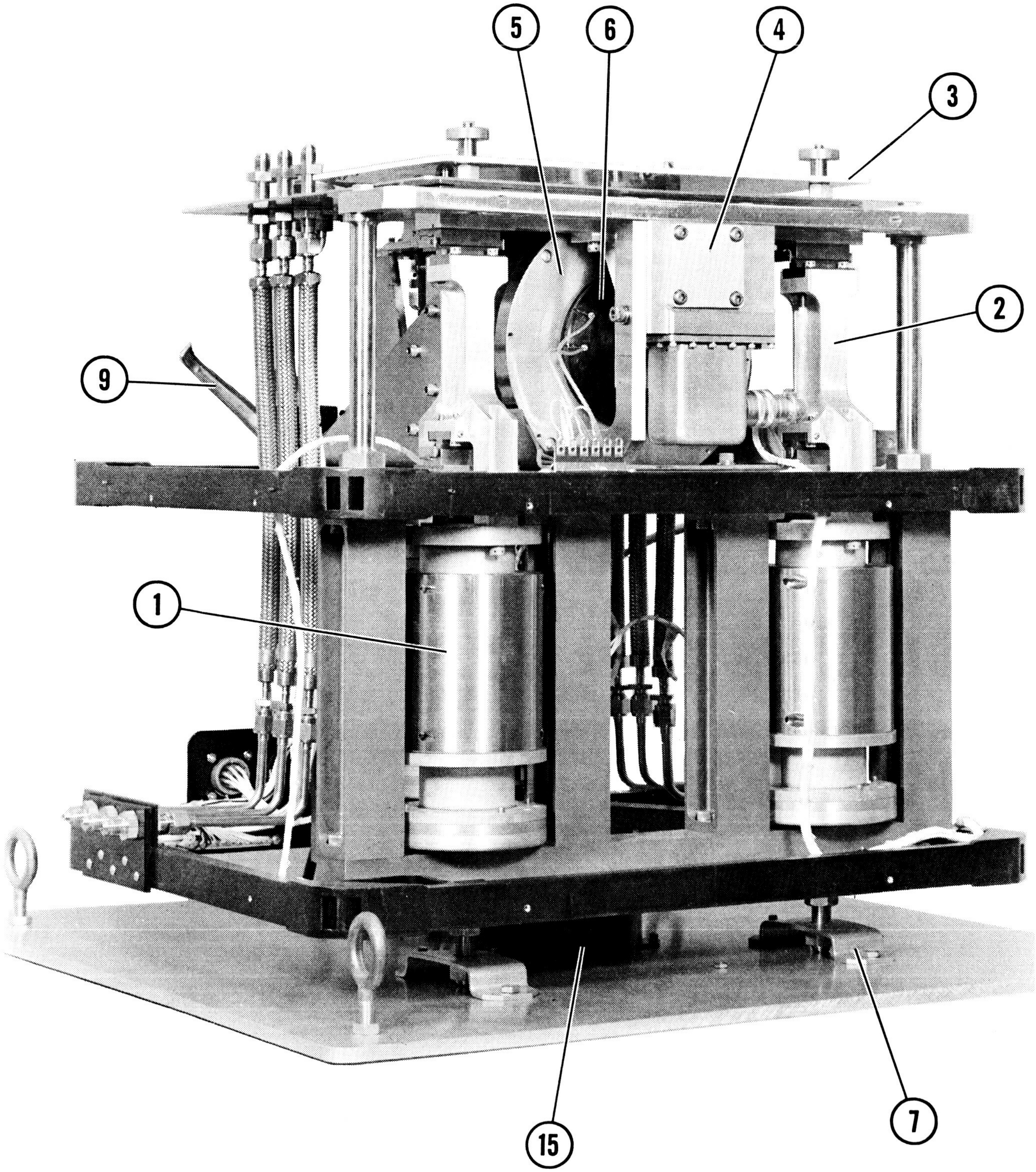

Fig. 2. Front view of the NASA thrust stand.

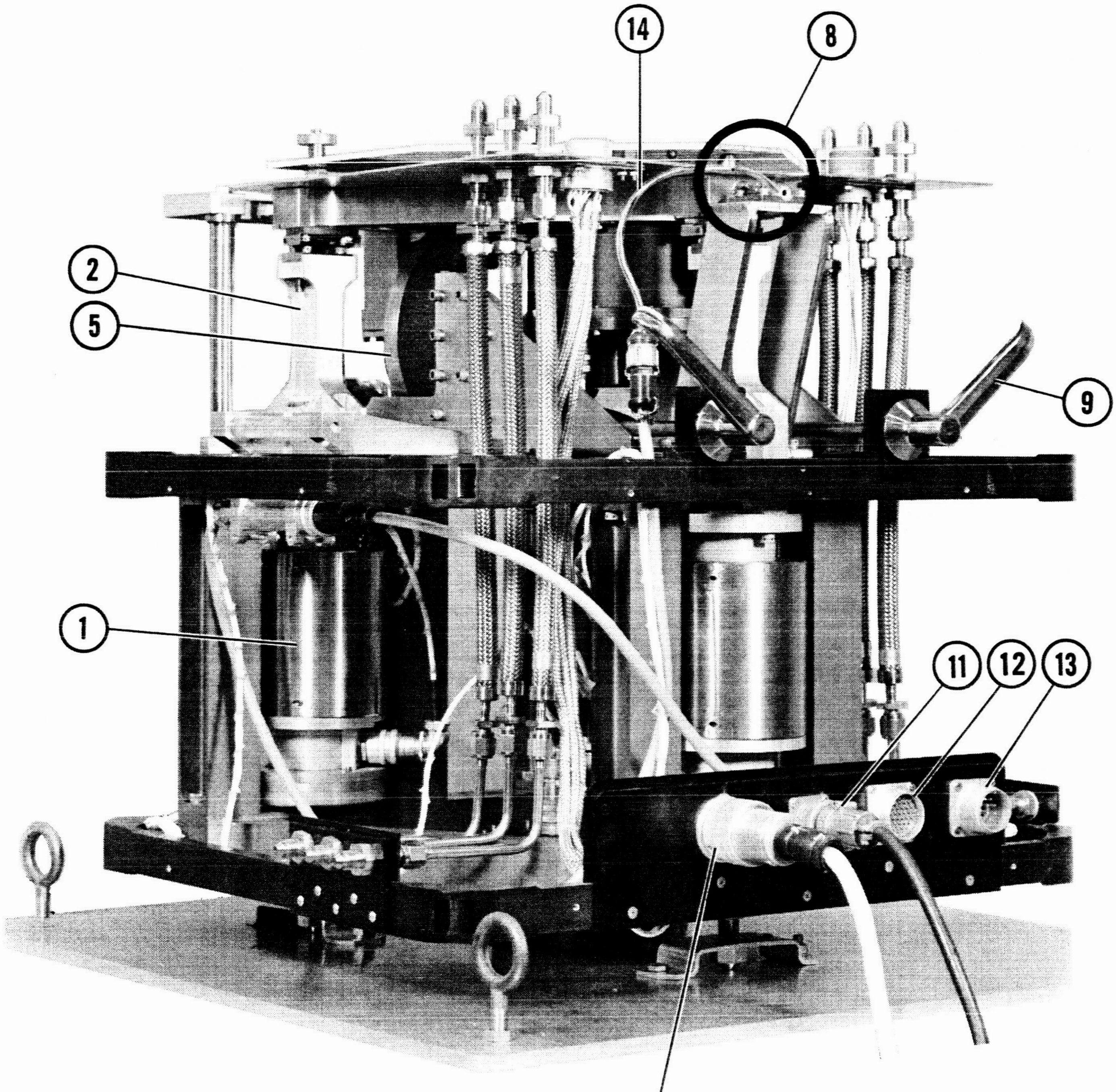

Fig. 3. Back view of the NASA thrust stand.

II. SYSTEM BLOCK DIAGRAM

The thrust stand system is shown in block diagram form in Fig. 4. The important features of this system can be followed by starting with the engine platform. Directly connected to the platform are a displacement transducer and a voice coil. Thrust of the test engine causes a horizontal platform displacement and results in an output signal from the displacement transducer. This signal is amplified and compensated to provide the driving current to the force motor to restore the platform to its null position. As shown in the block diagram, the signal output of the transducer is coupled to the Platform Control Network. This module includes four high quality chopper stabilized amplifiers and appropriate components to provide a restoring force motor current which contains proportional, derivative, and integral functions of the displacement signal. The control network also provides instrumentation readout of thrust, impulse, platform displacement, and internal test points. A dual channel "hot-wire" recorder provides a permanent record of all test results. A four place digital voltmeter is provided for accurate readout of all data under steady-state conditions.

The console instrumentation required for routine operation is shown in the lower right corner of the block diagram. All functions are individually discussed in the following sections of this manual (see Section V).

An important mechanical feature of the thrust stand is indicated in the block diagram as three weighted pendulums. The purpose of this type of suspension is to provide coupling from the engine system to the vacuum chamber in such a way as to permit accurate thrust measurements in a vibration background. The weight and moment arm of the counterweights are adjusted to provide a zero moment condition about the lower knife-edges. This is the equivalent of coupling the engine system to the vacuum tank at the system center of gravity. Engine thrust results in angular movement about the lower knife edge and can be instrumented directly.

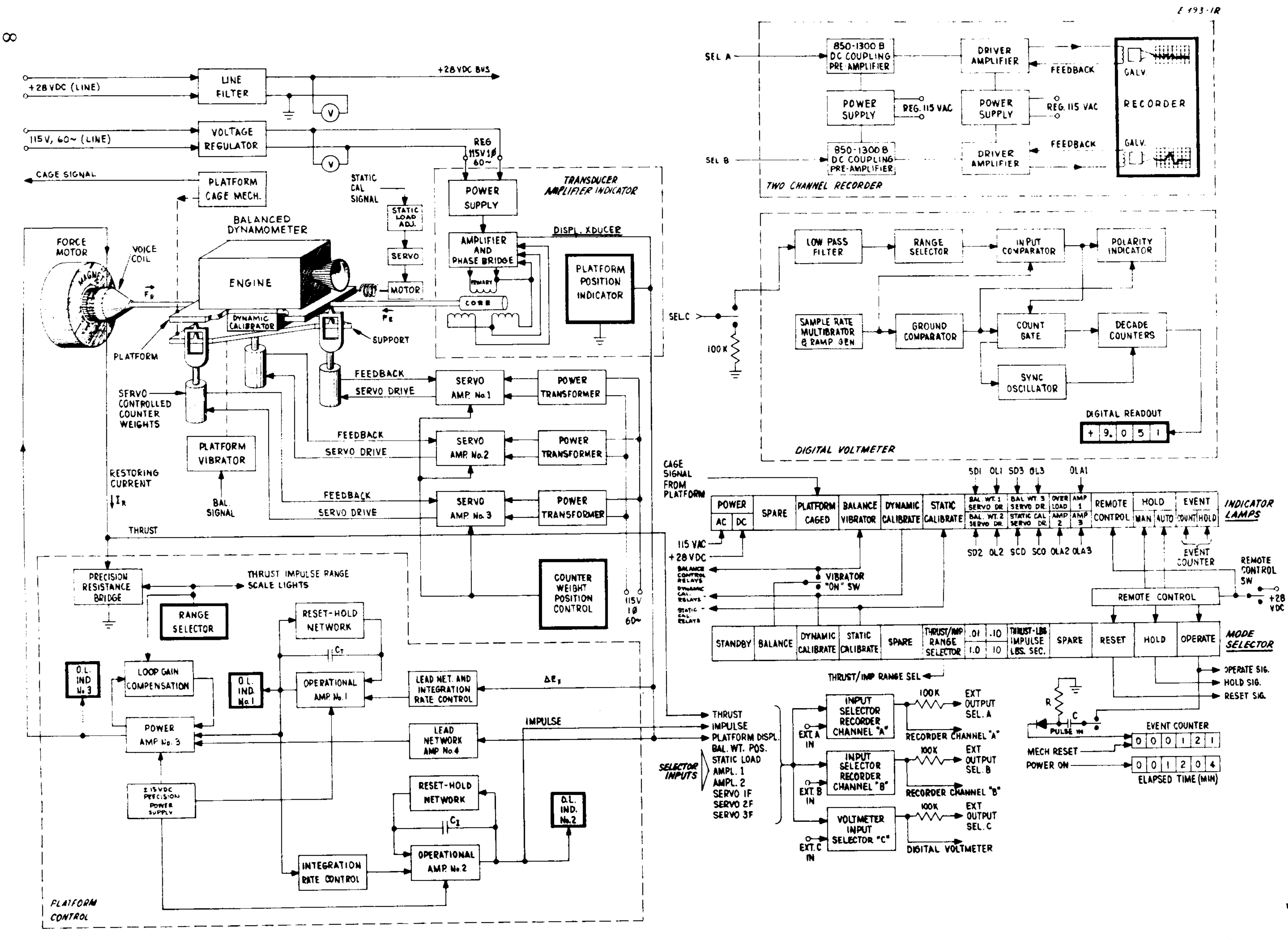

Fig. 4. Thrust stand system block diagram.

III. THRUST STAND PLATFORM

The basic thrust stand mechanism, shown in Fig. 5, consists of a movable platform supported by three compound pendulums mounted on a dimensionally stable tool steel frame. Virtually frictionless movement, of the platform with respect to the support structure, is obtained by use of precision knife edge bearings and bearing blocks.

An 11% chromium grade of tool steel was selected as the basic structure to provide the highest possible degree of dimensional stability in conjunction with an acceptable level of corrosion resistance. This structure is made up of two triangular frames separated by six columns bolted together with 1/4-28 screws. Each part is rough machined, stress relieved, final machined, heat treated, and precision ground. Processing and final grinding of the precision surfaces results in parts analogous in dimensional accuracy to gauge blocks.

M-2 tool steel heat treated to R_c 64 is used for bearing blocks (Fig. 6) on both the structure and the movable platform. The bearing blocks are rough machined, heat treated, ground, and lapped to provide a 4 μin. finish on the bearing contact surface with the critical dimensions being held to a tolerance of $\pm$ 0.000025 in.

The knife edge bearings are made of 440C stainless steel heat treated to R_c 60. Processing and finishing operations are similar to those used on the bearing blocks to provide comparable accuracy and surface finish. These bearings are then mounted in pairs on each of the three aluminum pendulums, and aligned to within $\pm$ 0.000025 in. of their common reference.

Aluminum is used for the pendulums as well as for the movable platform to minimize the system moving mass. These parts are precision machined, after rough machining and stress relieving, to meet a dimensional tolerance of $\pm$ 0.0001 in. on all critical dimensions. Critical bearing adjustments on the aluminum parts are made using a setup that permits adjustment and checking without personal handling (since heat transfer from the technician's hand to the part is sufficient to cause nonrepeatable settings).

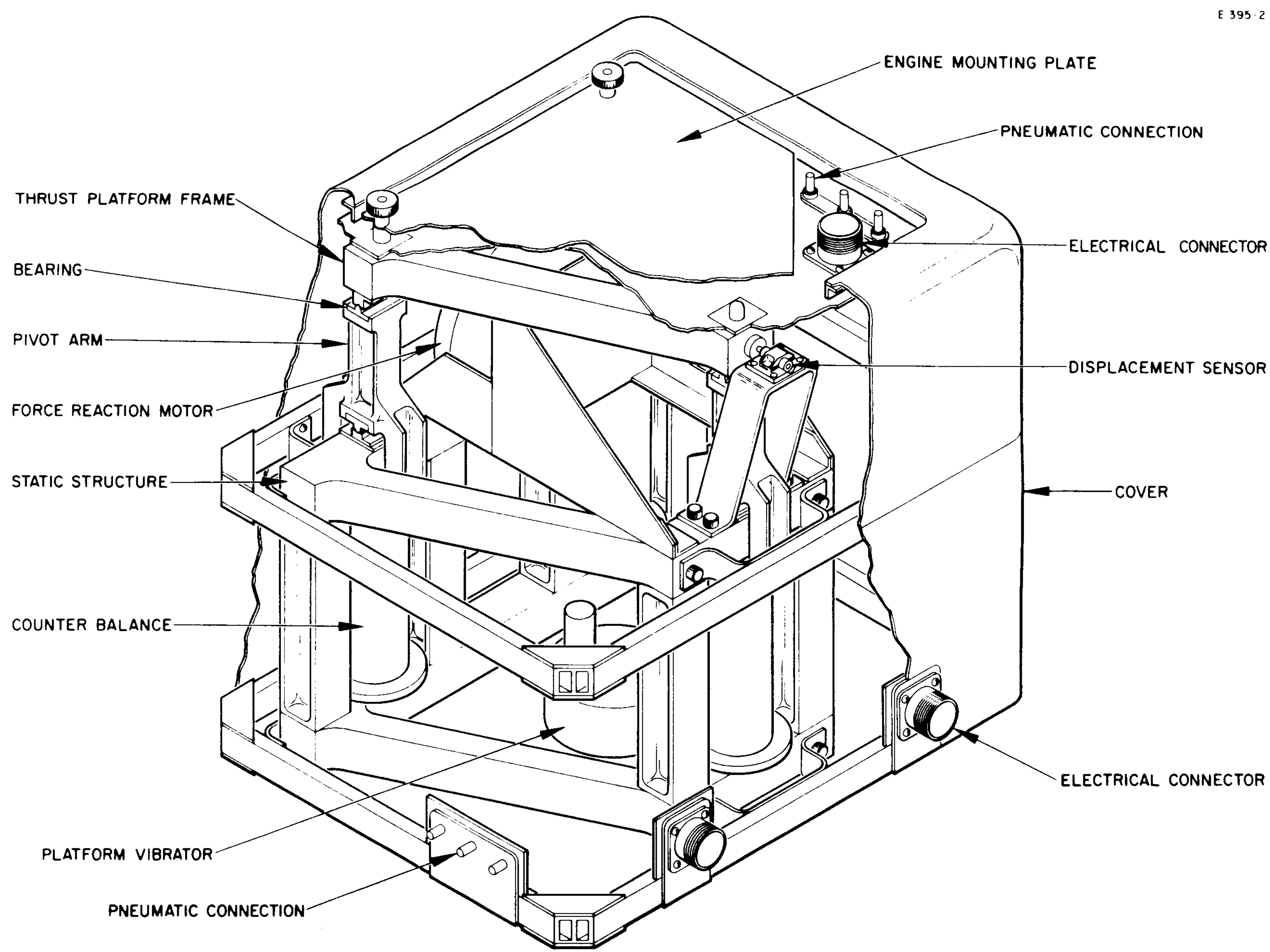

Fig. 5. Mechanical schematic of the balanced moment thrust stand.

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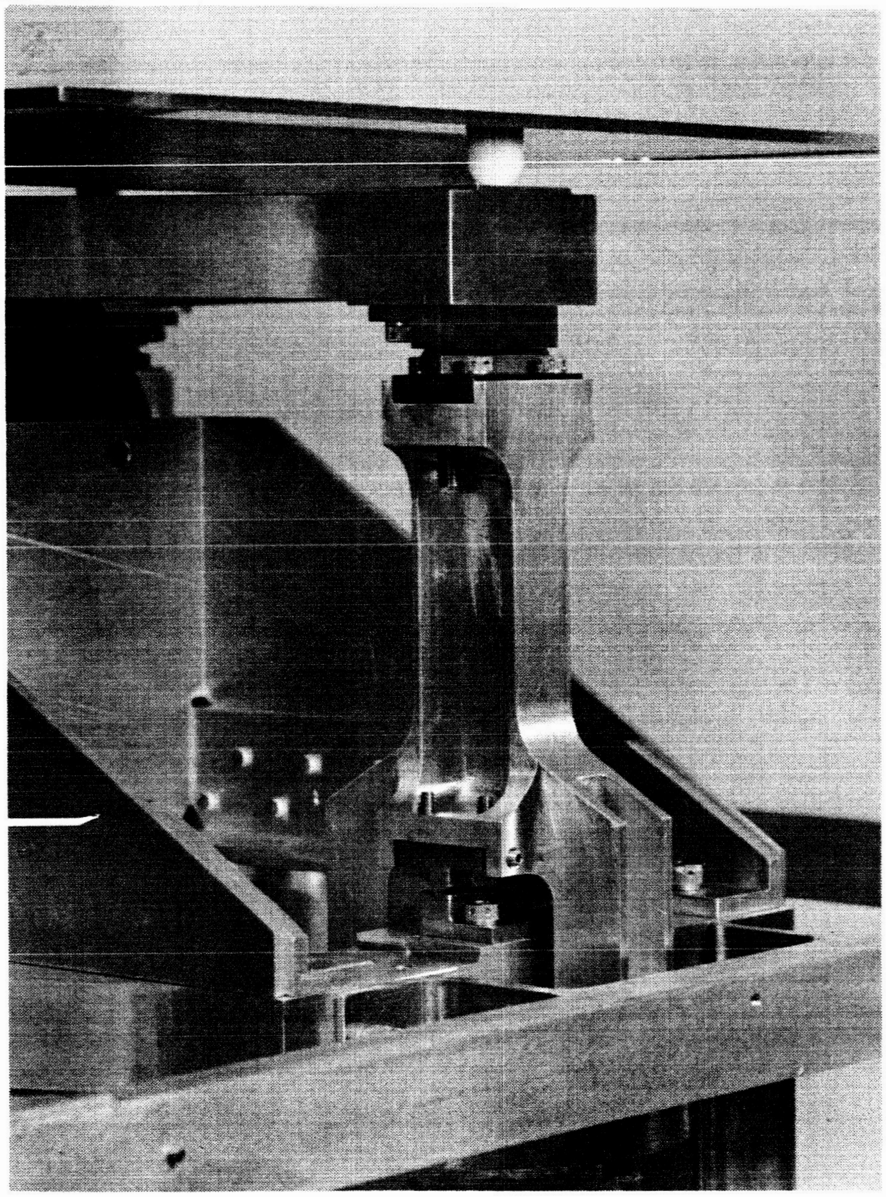

Fig. 6. Knife edge bearings and bearing blocks for thrust stand platform.

IV. SYSTEM ANALYSIS

A. General Characteristics

1. Physical Characteristics

The thrust measuring system has been designed for testing of chemical, subliming and cold gas thrustors. The test platform will accommodate thrustor packages weighing from 2 to 25 lb with package envelopes up to 12 in. long by 10 in. wide by 10 in. high. Electrical signal leads (25 pairs) are attached between the mounting platform and the support structure to permit thrustor control.

2. Performance Characteristics

Thrust range - 0.01 to 5.0 lb

Thrust threshold - 0.005 lb

Scale range - 10:1

Error $\leq 1\%$ of the upper limit of the range setting

Natural frequency - greater than 100 cps with 5 lb weight on thrust stand

Thrust stand calibration - static and dynamic calibration of balanced platform, zero set null of amplifiers and control loop balance

3. Environmental Requirements

The thrust stand is designed to withstand the following environmental conditions.

1. Vacuum to 10^{-7} Torr
2. Background vibration of 10 mg peak to peak at 1 cps in three orthogonal axes.
3. Temperature of $-60^{\circ}F$ to $+300^{\circ}F$
4. Humidity during storage of 95 %RH at 120° F

4. Data Display

All accessory equipment deemed necessary for instantaneous and recorded test data are supplied.

1. Displacement tranducer position indicator
2. Digital voltmeter read-out:
   a. Power supply voltage
   b. Thrust
      (1) 0 ⟶ 0.0100 lb
      (2) 0 ⟶ 0.1000 lb
      (3) 0 ⟶ 1.0000 lb
      (4) 0 ⟶ 5.000 lb
   c. Amplifier outputs
3. Two channel oscillograph

B. Analysis of the Balanced Dynamometer

The physical equations describing the dynamics of the balanced dynamometer are derived from basic laws of dynamics. The displacement equations are derived from the geometry of the platform. Consider the simple schematic diagram of the balanced platform shown in Fig. 7. The displacement of the platform is referenced to the null position of the upper pivot (point 1) and the displacement of the counter weight is referenced to the null position of its center of mass (point 2). By the nature of the platform design, the mechanism is free to rotate <u>about</u> the lower pivot point or axis of rotation (0) but is restricted from displacement <u>along</u> the axis of rotation.

Writing the displacement equation we have

$$\Delta x_1 = \ell_1 \sin \phi = \ell_1 \sum_{n=1}^{k} (-1)^{n-1} \frac{\phi^{2n-1}}{(2n-1)!}$$

$$\Delta y_1 = \ell_1 (1-\cos \phi) = \ell_1 \sum_{n=1}^{k} (-1)^{n-1} \frac{\phi^{2n}}{2n!}$$

$$\Delta x_2 = \ell_2 \sin \phi = \ell_2 \sum_{n=1}^{k} (-1)^{n-1} \frac{\phi^{2n-1}}{(2n-1)!}$$

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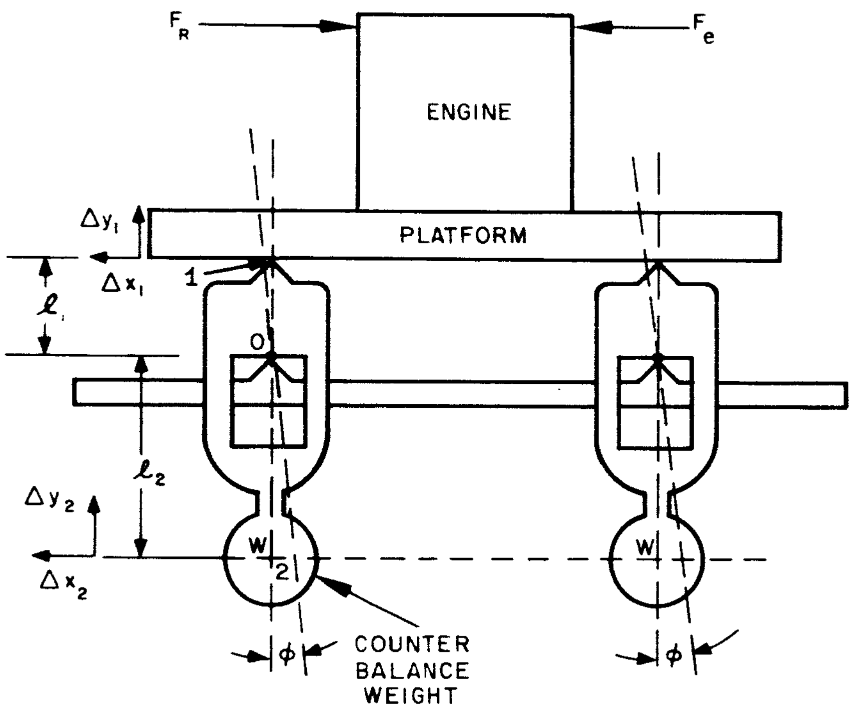


Fig. 7. Balanced moment dynamometer.

$$\Delta y_2 = \ell_2 (1 - \cos \phi) = \ell_2 \sum_{n=1}^{k} (-1)^{n-1} \frac{\phi^{2n}}{2n!}$$

If we mechanically limit the maximum horizontal displacement of the platform to 0.010 in. and provide equal linkage arms ($l_1 = l_2$) of 6.000 in. the maximum angular deflection ϕ is set at

$$\phi = \sin^{-1} \frac{x_i}{\ell i} < 0.5^\circ$$

As a result of the very small angular displacement, an approximation can be made to the sine and cosine series expansions with a good degree of accuracy, i.e.,

$$\Delta x_i = \ell_i \sin \phi \approx \ell_i \phi \left(1 - \frac{\phi^2}{6} + \frac{\phi^4}{120}\right)$$

$$\Delta y_i = \ell_i (1 - \cos \phi) \approx \frac{\ell_i \phi^2}{2} \left(1 - \frac{\phi^2}{12} + \frac{\phi^4}{360}\right)$$

Further, if we provide fast closed loop control of the mechanism such that the maximum displacement never exceeds 100 μin. for maximum thrusting force, the displacements may be accurately approximated by

$$\Delta x_i \approx \ell_i \phi$$

$$\Delta y_i \approx \frac{\ell_i \phi^2}{2}$$

$$\frac{\Delta y_i}{\Delta x_i} \approx \frac{\phi}{2}$$

In simplest form, the dynamics of the balanced moment dynamometer can be approached from the simple moment diagram shown in

Fig. 8. For small force differentials, the system will displace within the confines of the mechanical limits. To inhibit the angular acceleration and speed and to restore the platform to its null position, a restoring force (F_R) is generated by a permanent magnet motor. The restoring force is applied to the thrust platform in vector opposition to the thrust force (F_E).

By providing a high speed control loop around the thrust platform, the restoring force is generated almost at the same instant the platform begins to move from its null position. As a result, full platform restoration force is applied before the platform has traversed more than a few hundred thousandths of an inch (approximately 40 μ in for 5 lb of thrusting force). When the platform angular velocity is zero, a force balance ($\Delta F = 0$) condition exists across the platform and the relative position of the platform is either at the null or at some constant offset.

1. Operation

The engine thrust measuring instrument is essentially a precision balance of horizontal forces. Before measuring engine thrust the system must be balanced by precision adjustment of the counter-weights to eliminate the effects of environmental vibrations such as might result from vacuum pumps, seismic disturbances, etc., and then calibrated.

Referring again to Fig. 7. we note that initiation of engine thrust produces a force unbalance across the platform and the system begins to rotate about the system balance point (0) producing horizontal and vertical motions of the upper reference axis (point 1). Dynamic counterbalance of engine force and restoring force is attained almost instantaneously from a force-producing permanent magnet motor. The balanced dynamometer thus functions on the principle that the summation of horizontal forces across the platform is equal to the total mass of the platform and load times its horizontal acceleration.

$$\sum_{i=1}^{n} \vec{F}_i = M \ddot{\vec{x}}$$

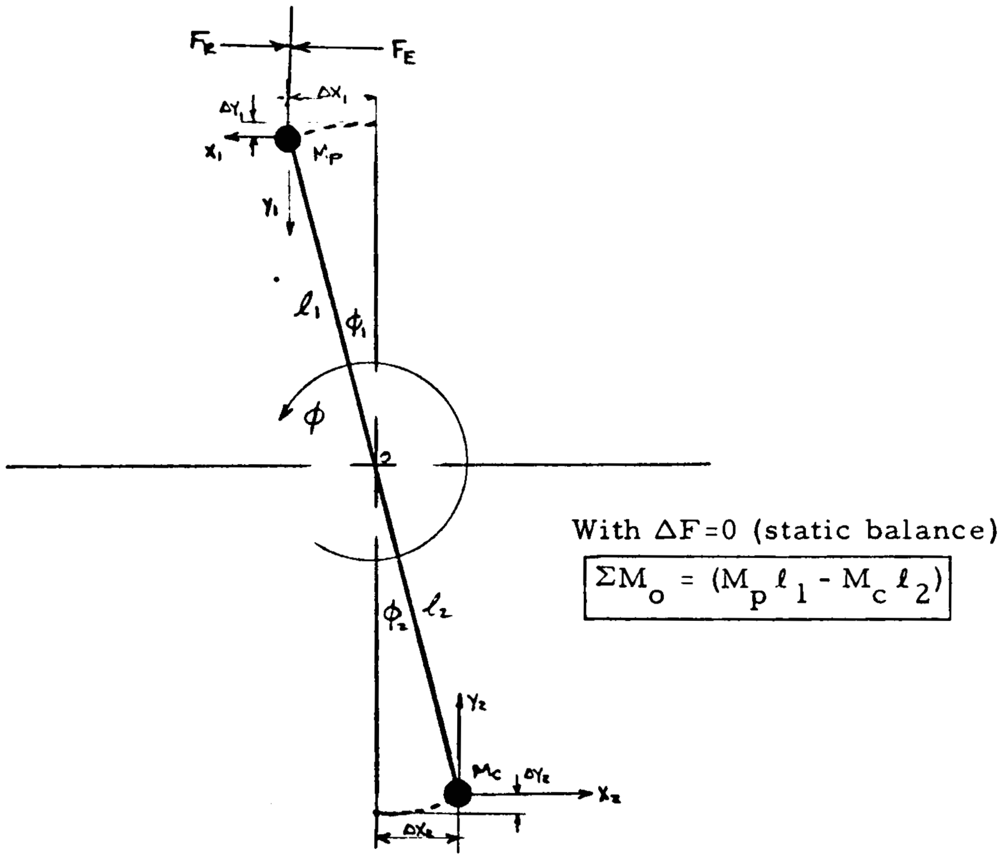


Fig. 8. Balanced moment diagram.

2. Analysis

The following physical equations describe the horizontal dynamics of the thrust platform during an engine thrusting condition. These equations are based on the assumption that the platform has been previously balanced in an engine nonthrust condition so that platform vibrations due to background vibration have been completely balanced out.

$$(F_E - F_R) = M\ddot{x} + B\dot{x} + Kx$$

$$x_1 = \ell_1 \sin\phi \approx \ell_1 \phi$$

$$\dot{x}_1 = \ell_1 \cos\phi\,\dot{\phi} \approx \ell_1 \dot{\phi}$$

where

F_E	=	engine thrust force, lb
F_R	=	platform restoring force, lb
M	=	total mass of system lb-sec^2/in.
B	=	velocity damping lb-sec/in.
K	=	spring rate lb/in.
$\ddot{x}$	=	horizontal acceleration
$\dot{x}$	=	horizontal velocity
x	=	horizontal displacement

Linearizing and LaPlace transforming the force balance equation yields the linear operator expression

$$\Delta F(S) = (MS^2 + BS + K)\,\Delta x(S)$$

Since the thrust platform is designed to have zero mechanical spring force K in the direction of thrust measurement, the spring force term may be eliminated and the above linear equation becomes

$$\frac{\Delta x(S)}{\Delta F} = \frac{1/B}{S(T_1 S+1)}$$

where

$$T_1 = M/B \text{ sec} \quad .$$

The resulting linearized differential equation for the thrust platform shows that the device is basically a mechanical integrator.

To achieve high speed operation we close loop control the platform mechanism which is designed to meet the following requirements:

1. The dynamic response of the control system with a 5 lb weight load on the platform will exhibit a natural frequency greater than 100 cps in all force ranges. The worst operating case being thrust cycling from 0.5 to 5.0 lb.
2. The threshold to the thrust stand is less than 10 mlb thrust.
3. The steady-state error of the thrust stand is less than 1% of the upper limit of each range setting.
4. The system is optimally damped for all ranges of thrust and for all weight loads and stable with a 25 lb weight load at all force ranges.
5. The system will measure thrust from 10 mlb to 5.0 lb.

3. Control

Since the thrust platform is basically an integrator device, the platform will continue to displace so long as a force unbalance exists across the platform or until the mechanical limits of the mechanism are reached. To provide a restoring force feedback (F_R) to return the platform to its steady-state null position during engine thrusting, it is necessary to provide a voltage integrator to generate a restoring voltage (E_R) to the restoring motor that is a function of the time integral of the displacement away from the null position. Displacement (ΔX) of the platform causes an error voltage (ΔEx) to be generated in the transducer output. This error voltage is then integrated to provide a restoring voltage (E_R) to the force motor which generates the restoring force (F_R). When the horizontal forces across the platform are balanced, the platform s restored to the null position. The addition of a voltage integrator into the control loop results in excessive loop phase shift and resulting system instability. Therefore, in order to provide a high speed system response with a high degree of stability, it becomes necessary to introduce a proportional plus derivative compensating network in parallel with the voltage integrator.

Consider now the transfer function block diagram of this system (Fig. 9). The <u>open loop transfer function</u> for the linear system is

$$K_o \, GH(S) = \frac{K_o \left(S^2 + a_1 S + a_2\right)}{S^2 (S + \omega_1)}$$

where

$$K_o = \left(\frac{P}{M}\right)\left(\frac{\delta E_x}{\delta x}\right) \text{ rad/sec}$$

$$\omega_1 = B/M \text{ rad/sec}$$

$$a_1 = K_p/K_D \text{ rad/sec}$$

$$a2 = K_I/K_D \,(\text{rad/sec})^2$$

The roots of the lead network for $K_I = 1$, $K_D = 1$, and $K_p = 500$ are

$$\sigma = -250 \pm \frac{1}{2} \sqrt{25 \times 10^4 - 4}$$

$$\sigma_1 = \epsilon \approx o; \quad \sigma_2 \approx -500 \quad \text{rad/sec.}$$

The open loop transfer function is thus

$$\frac{F_R(s)}{F_\Sigma} = \frac{K_o (S + \sigma_1)(S + \sigma_2)}{S^2 (S + \omega_1)}$$

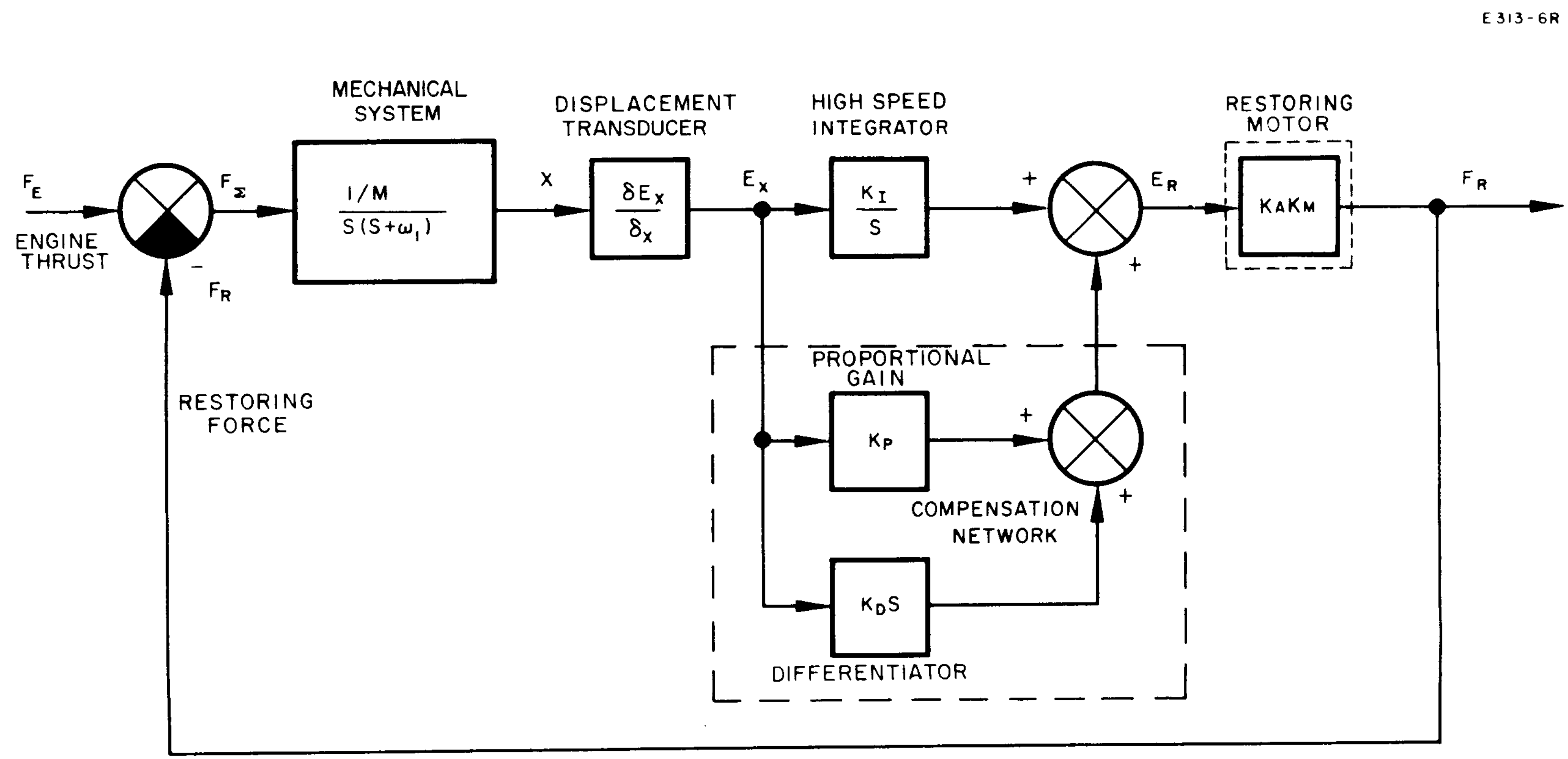


Fig. 9. System block diagram.

Assuming

$$\omega_1 = \frac{B}{M} \leq 80 \text{ rad/sec},$$

then

$$\frac{F_R(S)}{F_\Sigma} = \frac{K_o \ (S+\epsilon)(S+500)}{S^2 (S+80)}$$

A plot of the root locus of the open loop transfer function is shown in Fig. 10. The percent overshoot when the system is subjected to a step input can be easily estimated by referring to Fig. 11. For a damping factor $\xi = 0.7$ the overshoot is near zero. For higher values of damping factor it is noted that the system is heavily damped. For lower values of damping, the system is under damped. For operation at a damping factor of 0.7, the over-all system natural frequency (ω_n) is approximately 690 rad/sec or 110 cps, as shown in Fig. 10.

$$\omega_n = 690 \text{ rad/sec} = 110 \text{ cps}$$

$$\xi = 0.7$$

$$K_o = 960 \text{ (rad/sec)}^2$$

The power gain to the restoring motor will determine the frequency response of the system; for a 110 cps natural frequency with a 10 lb load on the thrust platform, the combined gain of the transducer and the power amplifier to the restoring motor must be

$$P\left(\frac{\delta E_x}{\delta x}\right) = K_o \ W/g = 17.9 \text{ lb/in.}$$

This system will provide a stable system response for any finite value of mass. For very large mass values on the order of several

K	ξ	ω_n
960	0.7	690
1,180	0.8	790
1,500	0.9	890

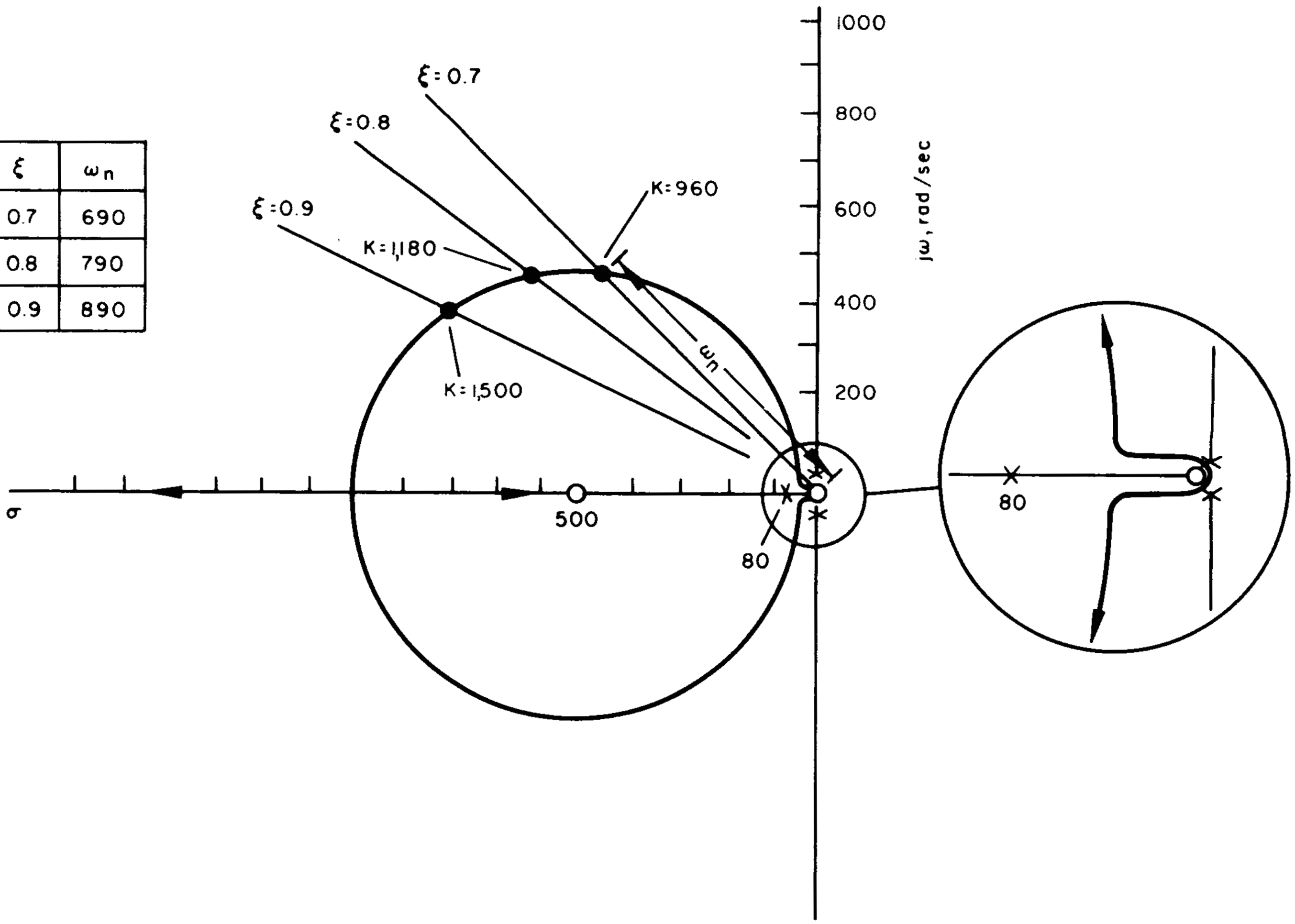


Fig. 10. Root locus plot of open loop transfer function.

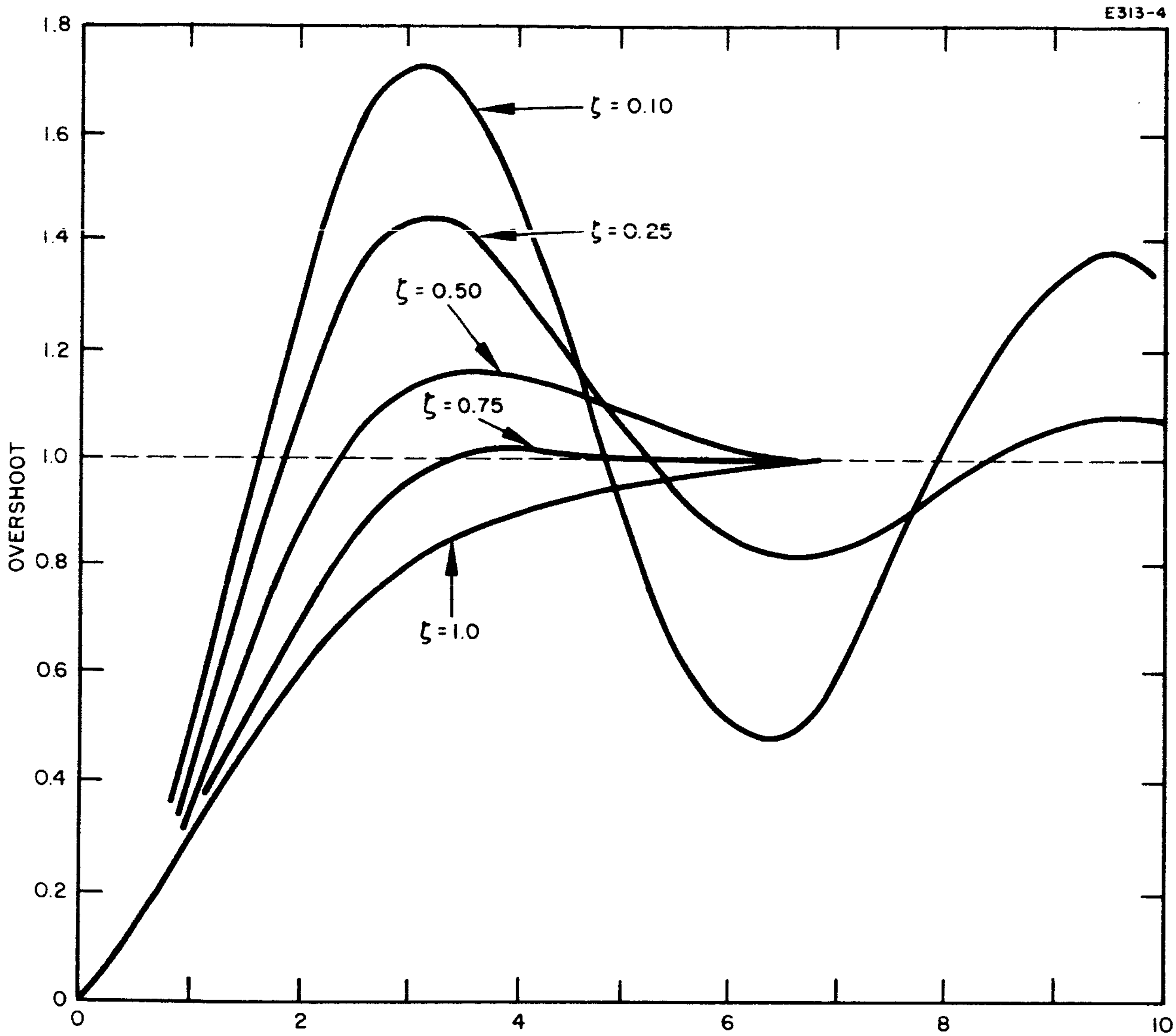


Fig. 11. Unit step-function response for system with transfer function $\omega_s^2/(s^2 + 2\zeta\,\omega_n s + \omega_n^2)$.

hundred pounds, the system will exhibit damped oscillations when subjected to a thrust step input. For values of mass up to 10 lb, the system will be heavily damped. This system further provides for the worst case conditions where the mass M becomes very large or where the damping B is very small. Consider now the limiting cases:

(1) $M \rightarrow$ large, $B \rightarrow$ finite, $\omega_1 \rightarrow$ small.

The open loop transfer function is

$$\frac{F_R(S)}{F_\Sigma} \approx \frac{P}{B} \left(\frac{\delta E_x}{\delta x}\right) \frac{\left(T_2 \; S + 1\right)}{S^2},$$

and the system is stable for any gain

(2) $M \rightarrow$ large, $B \rightarrow$ small, $\omega_1 \rightarrow$ small.

The open loop transfer function is

$$\frac{F_R(S)}{F_\Sigma} \approx \frac{P}{M} \left(\frac{\delta E_x}{\delta x}\right) \frac{\left(T_2 \; S + 1\right)}{S^2},$$

and the system is stable for any gain.

The natural frequency of the system ω_n can be increased by increasing the proportional gain term K_p or the loop gain K_o.

Assuming a perfect displacement transducer, the theoretical system will provide

1. A system natural frequency greater than 100 cps for mass loads up to 10 lb at a system gain of 960 $(\text{rad/sec})^2$ and damping factor of 0.7.

2. Negligible overshoot when subjected to a step in thrust.
3. Zero steady-state error (type 2 system)
4. Stable system response for platform loads up to several hundred pounds.

C. System Dynamics

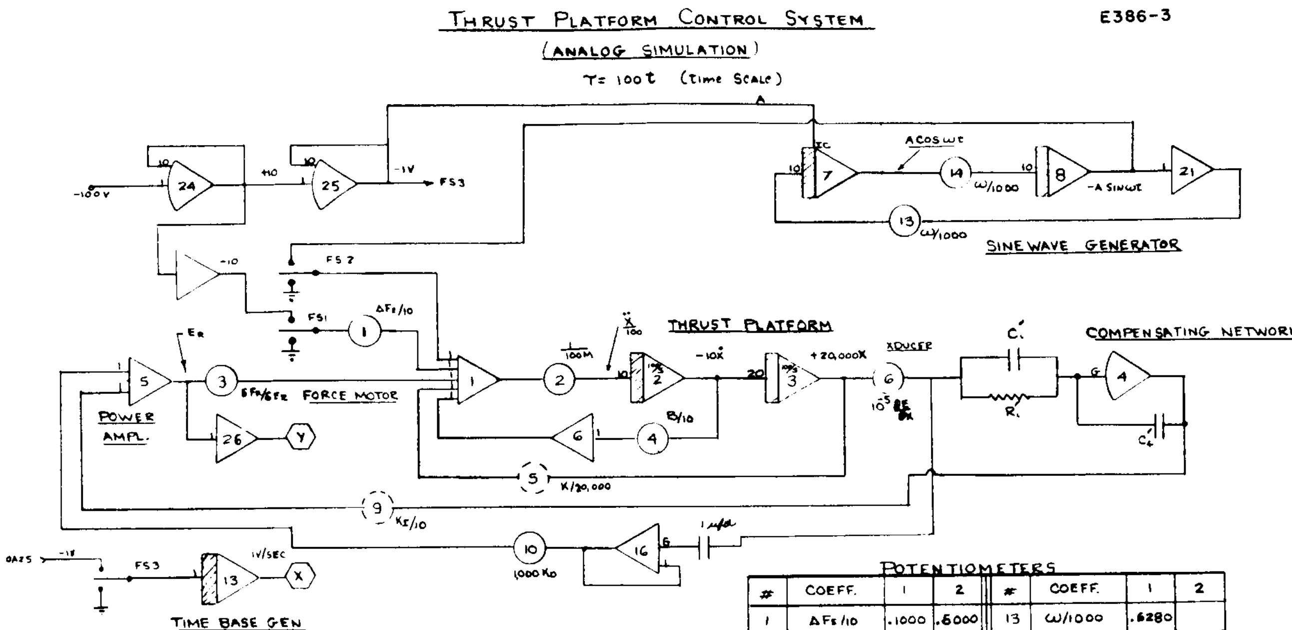
Analog simulation of the dynamics of the thrust platform and control system was conducted on the H. R. L. - PACE 16-31R general purpose analog computer. The analog mechanization of the system is presented in Fig. 12. The purpose of this study was to develop an electronic control system which would provide a fast, stable dynamic response for the balanced dynamometer system for all conditions of engine thrusting. The study included the determination of amplifier gains, sizing of the compensation networks, and the investigation of the over-all system transient behavior.

During the study, the analog model of the balanced dynamometer system was subjected to step changes in thrust. The resulting transient responses of the system restoring force (F_R) to engine thrusts of 1, 2, 3, 4, and 5 lb are presented in Figs. 13 and 14 with the salient characteristics of these results tabulated in Tables I and II.

1. Restoring Force Dynamics

The transient response of the theoretical system restoring force (F_R) to step changes in engine thrust (F_E) are illustrated in Fig. 13. This presentation shows the restoring force as a function of time after thrust bursts of 1 to 5 lb. The restoring force risetime (99% of steady state values), overshoot, and settling time (time for oscillations to settle to within 1% of steady state value) are tabulated in Table I.

The restoring force response to transient disturbances provides a fast, stable recovery of the thrust platform force balance. The slow decay of the restoring force overshoot results from the time required to return the platform to the null position. The estimated system damping factor ξ as determined from the overshoot is approximately 0.50.



POTENTIOMETERS

#	COEFF.	1	2	#	COEFF.	1	2
1	$\Delta F_E/10$	.1000	.5000	13	$\omega/1000$	.6280	
2	$1/100M$	.3860		14	$\omega/1000$	.6280	
3	$(\delta F_E/\delta E_R$	1.0000		15			
4	$B/10$	0		16			
5	$K/20{,}000$	0		17			
6	$10^{-5}(\delta E/\delta x)$	1.0000		18			
7				19			
8				20			
9	$K_I/10$	1.0000		21			
10	$1000\,K_D$	1.0000		22			
11				23			
12				24			

NETWORK

$C_i' = C_i = 1\,\mu fd$

$C_f' = 100 C_f = 1\,\mu fd$

$R_i' = 100 R_i = 2\,M\Omega$

Fig. 12. Analog mechanization of the thrust platform control system used to study the system dynamics.

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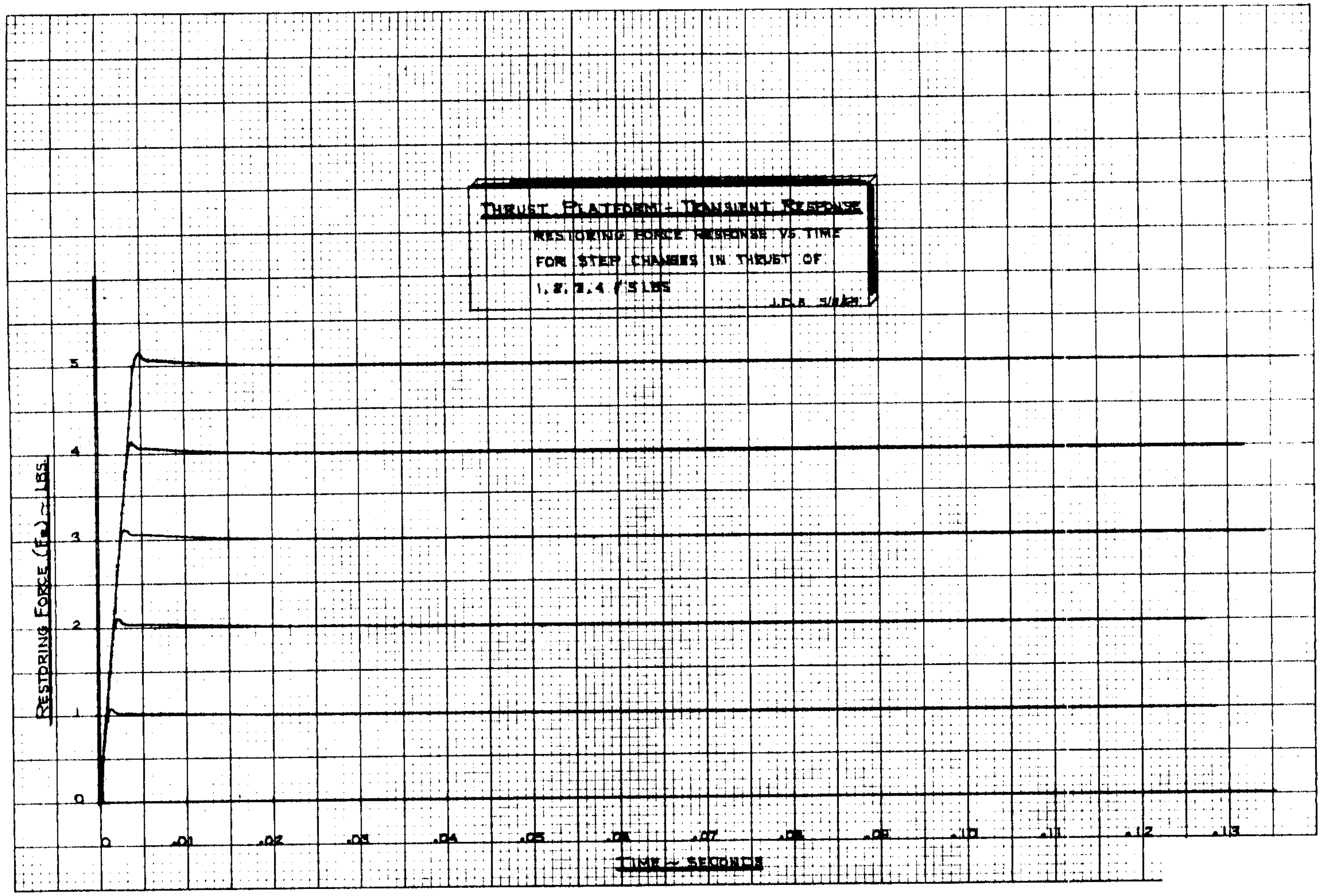

Fig. 13. Transient response of the system restoring force to step changes in engine thrust.

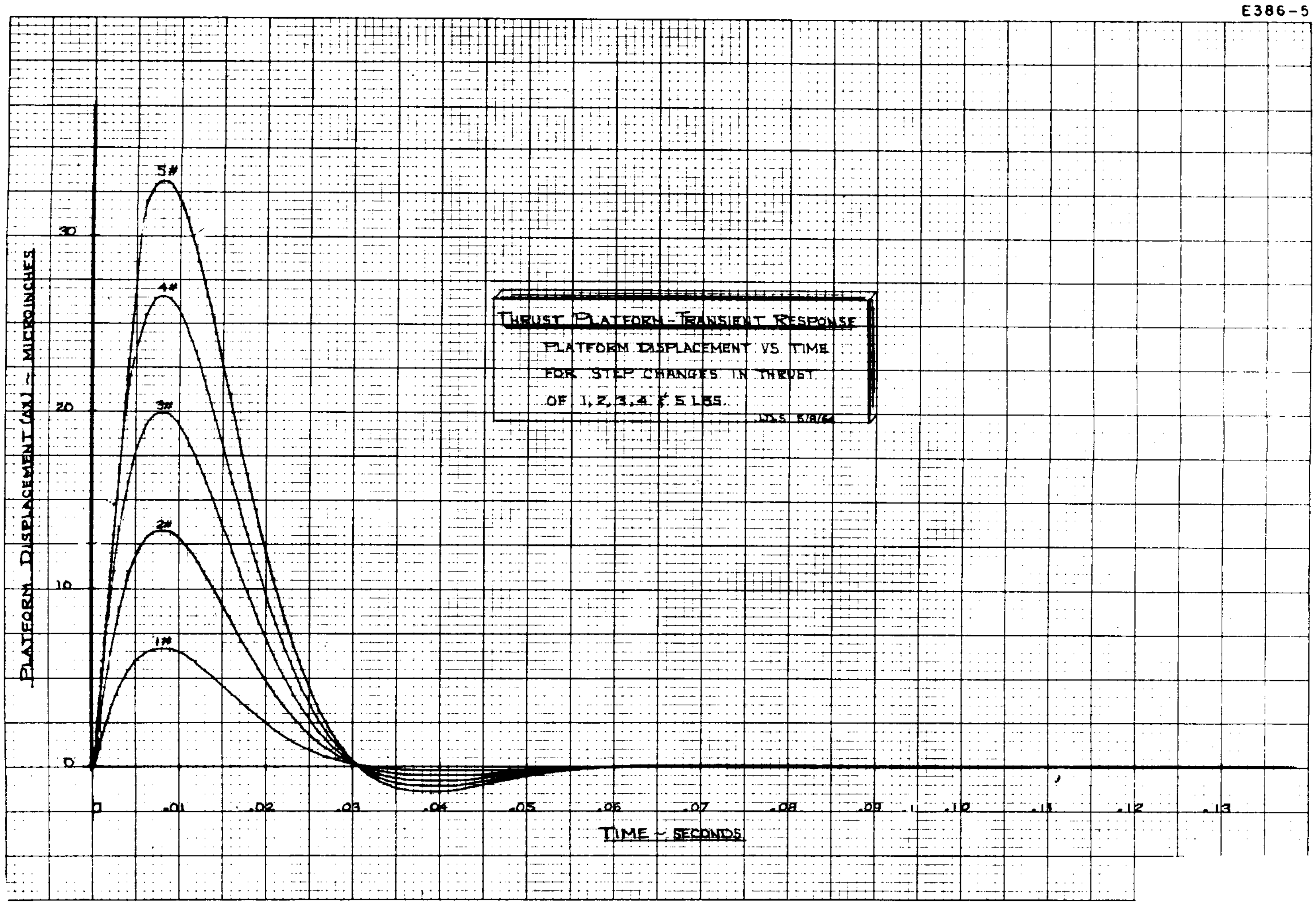

Fig. 14. Thrust platform displacement response to step changes in engine thrust.

TABLE I

Engine Thrust	Analog Solution Restoring Force		
Step Change, lb	Rise Time, msec	Settling Time, msec	Overshoot, %
1	0.8	8.0	< 9
2	1.6	8.0	< 5
3	2.5	8.0	< 4
4	3.3	8.0	< 4
5	4.1	8.0	< 3

2. Platform Displacement

The theoretical thrust platform displacement responses to step changes in thrust are illustrated in Fig. 14 with the salient results and characteristics tabulated in Table II.

TABLE II

Engine Thrust	Analog Solution Platform Displacement			
Step Change, lb	$\dot{x}$ max 10^{-3} in./sec	Δx max μin.	Overshoot, μin.	Approx. Response Time sec
1	1.7	6.6	0.25	0.03
2	2.7	13.3	0.50	0.03
3	3.4	19.9	0.75	0.03
4	4.0	26.5	1.0	0.03
5	4.5	33.2	1.4	0.03

The transient results shown depict the dynamic characteristics of the platform to step changes in engine thrust. For presently established control loop gain, the system will experience a slight negative overshoot (approximately 1.4 μin. for 5 lb thrust) at about 0.04 sec after the thrust burst.

The displacement characteristics show that the magnitude of displacement is proportional to its thrusting force.

$$\text{i.e.} \qquad \frac{\Delta x}{\Delta F_E} = 6.6 \ \mu\text{in./lb}$$

Thus, the negative overshoot for a thrust of 5 lb indicates an excess restoring force $(F_R - F_E)$ equal to

$$F_R \approx 0.2 \text{ lb (at the maximum undershoot),}$$

which in a very short time decays to zero.

This calculated value of excess restoring force is in close agreement with the value of overshoot illustrated in Fig. 13.

3. Transient Response

Figure 15 illustrates a composite of platform velocity ($\dot{x}$) and displacement (x). This method of data presentation is commonly referred to as a Phase Portrait. The ordinate of the diagram illustrates platform velocity and the abscissa illustrates the platform displacement. Consider now a typical response of the platform. At steady state, the platform is at its null condition ($x = o$, $\dot{x} = o$). A 5 lb engine thrust causes the portrait to move upward and to the right in Quadrant I, reaching a maximum velocity at 4.5×10^{-3} in./sec and continuing clockwise rotation into Quadrant IV. The system reaches maximum displacement as $\dot{x}$ goes through zero. The velocity-displacement characteristics continue to rotate clockwise until a steady state

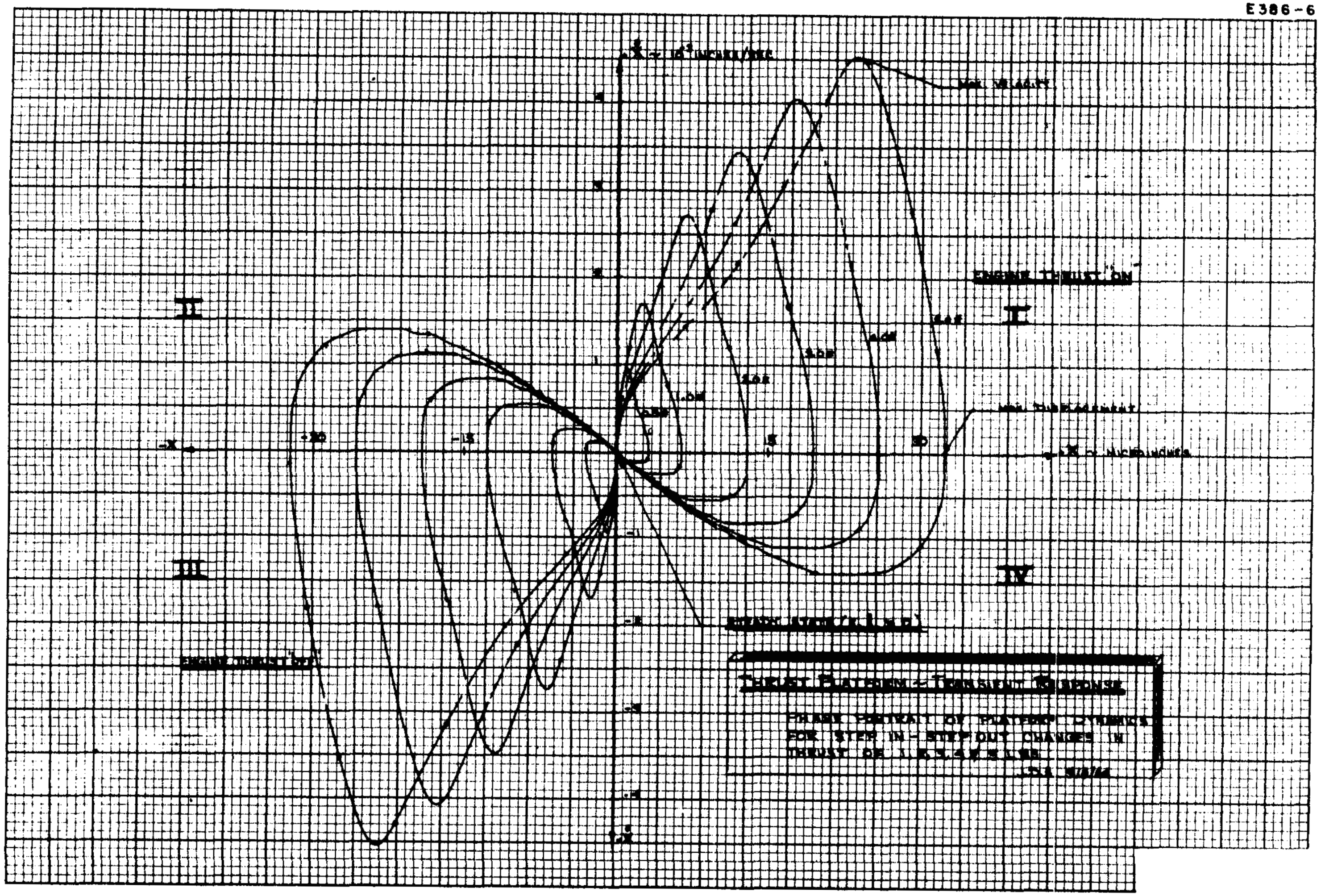

Fig. 15. Phase portrait of platform dynamics for step in - step out changes in thrust of 1, 2, 3, 4, 5 lb.

condition is reached at the null point. Once at zero, the system is at a steady state null condition with the engine thrusting continuously at 5 lb.

$$\text{i.e.} \quad F_R = F_E = 5 \text{ lb}$$

Termination of engine thrust (F_E = o) causes the portrait to rotate clockwise from null into Quadrant III. The system reaches maximum negative displacement at $x = 33\ \mu$in. ($\dot{x}$ = o). The system response now approaches the null condition from Quadrant II. At steady state, $x = o$, $\dot{x} = o$, $F_R = F_E = o$, and the system is ready for a new thrust cycle.

4. Steady State Response

A sinusoidal variation in thrust was applied to the theoretical system with a peak to peak amplitude of 2 lb at a frequency of 100 cps. The results of this input variation are illustrated in Fig. 16. The upper channel shows the sinusoidal thrust input. The second channel shows the platform displacement response with the third channel showing restoring force response.

The results indicate a good system response to a 100 cps thrust variation. The restoring force (F_R) experiences an approximate 15° phase lag and the displacement (x) experiences an approximate 100° phase lag with respect to the input.

$$\text{i.e.} \quad \Delta\phi F_R \approx 15^\circ$$
$$\Delta\phi_x \approx 100^\circ$$

As engine thrust comes up on the first half cycle, the platform is initially at its null position ($x = o$) with a restoring force of zero. The restoring force rapidly rises to meet the thrusting force with a finite time involved between the initial response of the platform and steady state-equal amplitude variations about the null. This time is approximately 0.03 sec.

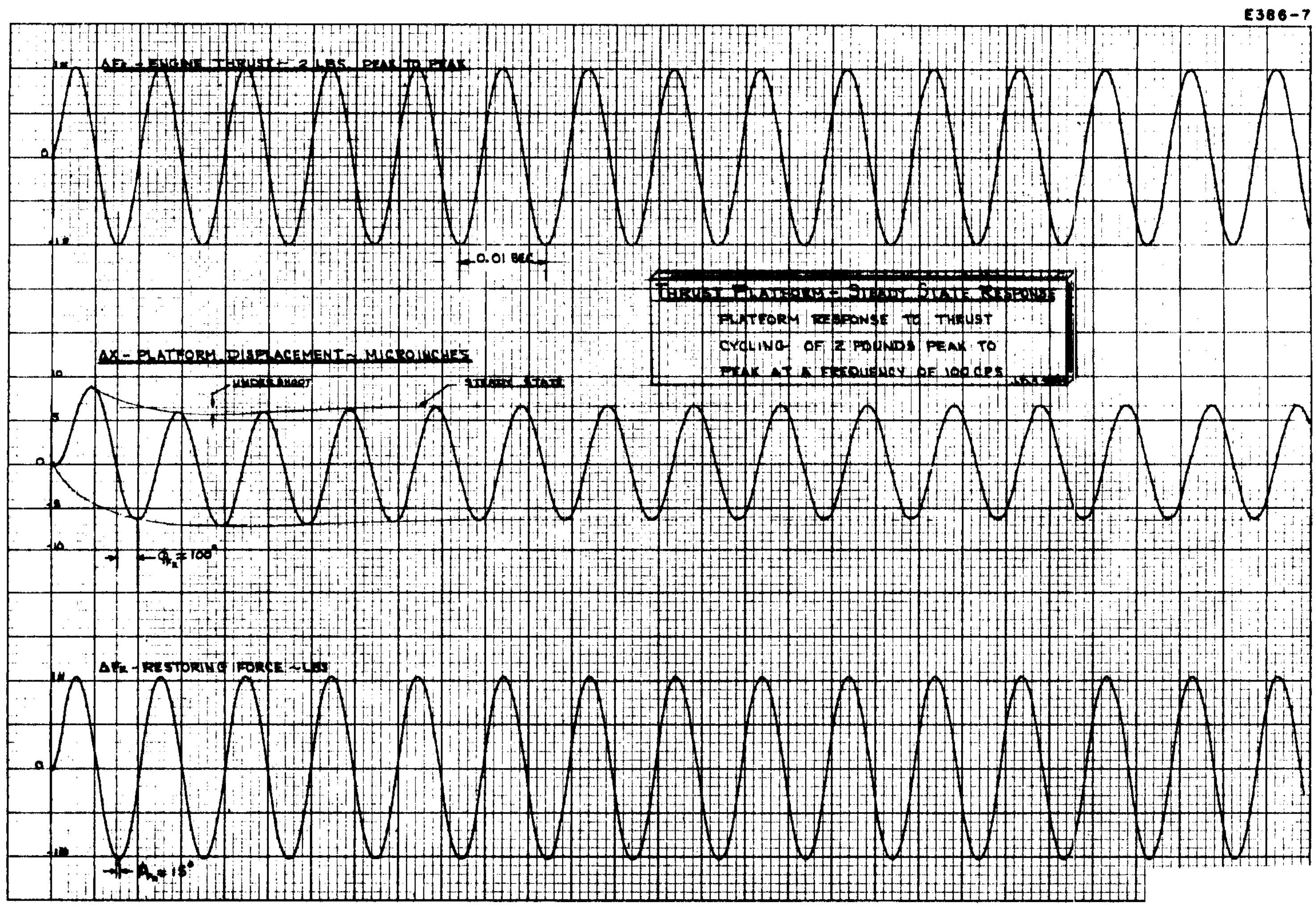

Fig. 16. Platform response to thrust cycling of 2 lb peak to peak at a frequency of 100 cps.

Steady state gain of the theoretical system for a 2 lb, 100 cps input signal is

$$A_{db} = 20 \log_{10} \frac{F_R}{F_E} = 20 \log_{10} \frac{2.075}{2.00} = 0.3 \text{ db} \quad .$$

Analytical results predict fast, stable system dynamics for all ranges of thrust.

V. CONSOLE CONTROL AND INSTRUMENTATION

A. Mode Selector

The operational control panel (Fig. 17) is provided with nine mode selector switches, one thrust range selector, twenty-four sets of indicator lamps, and seven function switches to furnish the operator complete control of the mechanism and instrumentation of the thrust stand during all phases of system operation. In the event of a component malfunction, the mode selectors and instrumentation indicator lamps serve as an invaluable aid in problem troubleshooting.

1. Standby Mode

When the main circuit breakers are disconnected from the control console, the system is in the "Off" condition and no external power is supplied to the system. Closing the main circuit breakers connects 115 V ac and +28 V dc to the control console instrumentation and mode control relay networks, and automatically places the system in the "Standby Mode" of operation. If the system has been turned off for a period of more than 1 hour, the system should then be allowed to remain in standby for approximately 20 min to allow the system instrumentation to come up to operating temperature.

During standby operation, the system is in the following state:

1. 115 V ac Power "On" (Instrumentation, etc.)
2. + 28 V dc Power "On" (Mode Control Relays)
3. ± 15 V dc Reference Voltage "Off"

The system can be returned to "Standby Mode" from any other mode by merely depressing the standby selector. Depression of the standby selector automatically clears all other mode selectors.

2. Balance Mode

In the "Balance Mode" of operation, the ± 15 V dc reference is connected to the computer circuitry, the front panel

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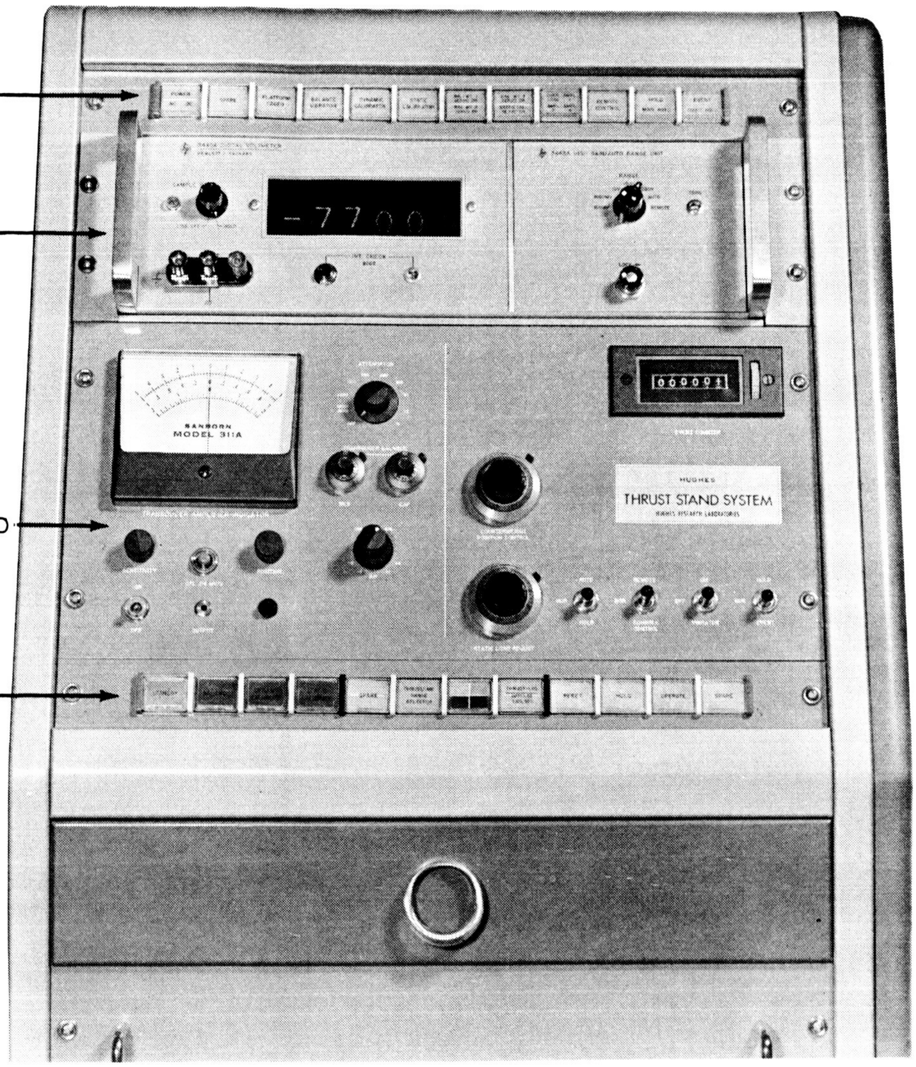

Fig. 17. Upper Right Panel.

Counter Weight Position Control and the counter weight position feedback potentiometers located within the three balance weight housings. With the thrust platform uncaged in the "Balance Mode", the mechanism is subject to forces resulting from background vibrations arising from seismic disturbances, vacuum pumps, vehicle traffic, etc., which results in variations on the highly sensitive Displacement Transducer Null Indicator. These oscillations will have an amplitude that is a function of the degree of dynamic balance of the counterweight system. Slewing of the vertical position of the counterweights will directly affect the degree of dynamic balance and the amplitude of oscillation. If a condition should arise in which the background vibrations are not of sufficient magnitude to produce a discernible indication on the null indicator, the auxiliary mechanical vibrator may be turned "On" to provide the necessary amplitude of mechanical vibration to dynamically balance the system. The mechanical vibrator provides a 2 lb, 2 cps sinusoidal vibration to the base of the stand.

The vertical positions of the servo controlled counterweights are determined by the resistance value set on the Counter Weight Position Control Potentiometer. Dynamic balance of the dynamometer system is indicated by a null or minimum in the vibration amplitude. At this time the Counter Weight Position Control is locked and the setting recorded for future reference.

Counterweight servo drive is indicated by a red light on the indicator panel. When the servo driven counterweights have reached the position corresponding to the dial setting of the Counter Weight Position Control, the red lamps will extinguish. A red lamp "On" in Servo Drives 1, 2, or 3 means that the corresponding servo has not reached steady state. The counterweights require approximately 60 sec to travel from the upper to the lower limit. Since the counterweight servo systems are identical, the three servo drive lamps should extinguish at approximately the same time.

3. Dynamic Calibrate Mode

When the system is switched to the "Dynamic Calibrate Mode" of operation, the system is energized in a mode similar to the "Operate Mode," since the control loop components are performing normal operate functions. The Dynamic Calibrator is automatically turned on in this mode and provides a constant amplitude, constant frequency, sinusoidal force variation on the platform.

The Dynamic Calibrator is basically a mechanical vibrator designed to provide a sinusoidal force along the thrust axis. When the synchronous drive motor is brought up to speed, two unbalanced weights are rotated in opposite directions coupling, a known vibration to the engine mounting platform. This sinusoidal force simulates an engine thrust variation of 1 lb peak at a frequency of 83 cps. The control loop gain is dynamically adjusted during this mode of operation for wide band frequency response.

4. Static Calibrate Mode

In the "Static Calibrate Mode" a Static Load Calibrator provides an adjustable steady force to the thrust platform. This mode is also similar to the "Operate Mode," meaning that the system is closed loop controlled with the computer elements. In this mode, the static load mechanism is introduced into the system to provide a simulated static force on the platform in the direction of normal engine thrusting. The static load mechanism is designed so that it may be precisely adjusted to within 1% throughout the normal thrust range with the Static Load Adjust control located on the front panel. The 15 V reference is connected to the Static Load Adjust potentiometer during this mode only.

Interchanging the static load capsules provided with this equipment allows the following static loads to be attained:

a. 0.01 → 0.1 lb
b. 0.1 → 1.0 lb
c. 0.5 → 5.0 lb

Calibration of the precision (0.1%) networks located in the Platform Control Network is performed in the Static Calibrate Mode, thereby calibrating the electrical readout of the thrust and impulse measurement against precision static forces from 10 mlb to 5 lb.

5. Reset Mode

The "Reset" or initial condition mode of operation primarily affects the function of electronic control system components. The "Reset Mode" is one of the three platform control operations, and provides the initial condition system state just prior to the "Operate" mode. In the "Reset Mode," the inputs to the integrator amplifiers are open circuited and an initial condition resistor voltage divider is applied across the charging capacitor. Under these conditions, an initial charge may be applied across the capacitor by switching in the initial condition networks (IC) of the thrust or impulse amplifiers. An initial charge will represent an initial thrusting force for the Thrust Amplifier and an initial impulse for the Impulse Amplifier. The "Reset Mode" returns the system to its ready condition by setting the initial condition on each of the control loop capacitors and clearing all relay operations to the ready position.

The outputs of the control loop operational amplifiers are also nulled in this mode by individually selecting each amplifier output on the digital voltmeter and zero setting the amplifier output with the screwdriver adjustment located on the front panel.

6. Operate Mode

In the "Operate Mode" all amplifier control relays (Hold, Balance, IC) are in the de-energized position, and all instrumentation circuitry is activated for the thrust and impulse measurements. Four ranges of thrust and impulse measurement are available in the "Operate Mode" (see Table III).

TABLE III

Various Ranges of Thrust and Impulse Measurement

Range	Thrust, lb	Impulse, lb sec
1	0.01	0.01
2	0.1	0.1
3	1.0	1.0
4	5.0	5.0

The four ranges provide maximum readout sensitivity for any given engine thrust level up to 5 lb.

Thrust-Impulse Range selection is made by depressing the Range Selector Switch, which sequences a rotary stepper switch located in the Thrust Impulse Range Selector Network. The stepper switch will change one scale for each depression of the selector switch. The corresponding Thrust-Impulse Range and units of measurement are indicated on the indicator panels.

7. Hold Mode

The "Hold Mode" of operation acts as a memory to hold the last computed voltage charge on the integrator capacitors. This in turn effectively holds the final value of Thrust and Impulse. When the "Hold" selection is made, the hold relay is energized and grounds the amplifier input summing junctions. With the inputs removed, the integrator amplifiers store the final value of voltage across the charge capacitor for several minutes with a high degree of accuracy regardless of subsequent engine operation. Estimated degradation of charge storage is less than 0.1%/sec during "Hold."

Preliminary wiring is provided for an auxiliary amplifier overload alarm circuit to automatically switch the system from "operate" into the "Hold Mode" whenever a sustained or intermittent overload occurs in any of the three operational amplifiers. This automatic hold feature would be used at the operator's option. Over-voltage overload is indicated on the overload indicators monitoring each of the control loop amplifiers.

B. Additional Control Functions

Several additional control functions are also available on this console. They are the Remote Control, Automatic Hold, Platform Vibrator, Event Counter, and Initial Condition. A brief description of these control functions is given herein.

1. Remote Control

When the Normal-Remote function switch is switched to "Remote," the three platform control operations, "Reset," "Hold," and "Operate," are transferred through control relays to the remote control station. In this mode of operation, the main console is slaved to the remote station. Temporary override of the remote station may be effected at the main console by depressing any of the operating mode selectors. Release of the selector immediately returns the system to the remote position control. To return the system control to the main console the operator must return the Normal-Remote function switch to the "Normal" position.

2. Auto/Normal Hold

The Auto/Normal Hold function switch provides for the future incorporation of an automatic hold circuit. When the Auto/Normal Hold function switch is in the up position, overload of any of the computer elements would automatically place the system in "Hold," thereby salvaging a part of the Thrust and Impulse data which might otherwise be lost. This circuit would also provide an automatic hold of the impulse measurement when the Impulse Range (± 10 V dc) is exceeded.

3. Platform Vibrator

The Vibrator On function switch turns on the 2 lb, 2 cps mechanical vibrator in the "Balance Mode" only.

4. Event Count

The Event Count function switch controls the operate pulse to the Event Counter. In the normal position, the event counter counts one digit each time the operate switch is depressed, thereby keeping a numerical count of the total number of operations. In the hold position, the Event Counter is disconnected and holds the current total. Reset to zero of the counter is done manually.

5. IC and Capacitor Short

The IC (Initial Condition) switches located on the front panel of the Thrust and Impulse Networks (Fig. 18) connect the Initial Condition circuitry to the Thrust and Impulse network. With the IC switch in the up position, an initial voltage charge from zero to 10 V may be set into Thrust and Impulse outputs.

The Capacitor Short switches are physically located in parallel with the Thrust and Impulse integrator capacitors. Either circuit may be disabled by merely shorting out its charging capacitor. It is recommended that the Impulse Capacitor Short switch be used to disable the Impulse Circuit when an impulse measurement is not being made; otherwise, the Impulse amplifier will drift into an overload condition. Although the amplifiers have a built-in overload protection feature, it is not considered good practice to leave them in an overload condition for long periods of time.

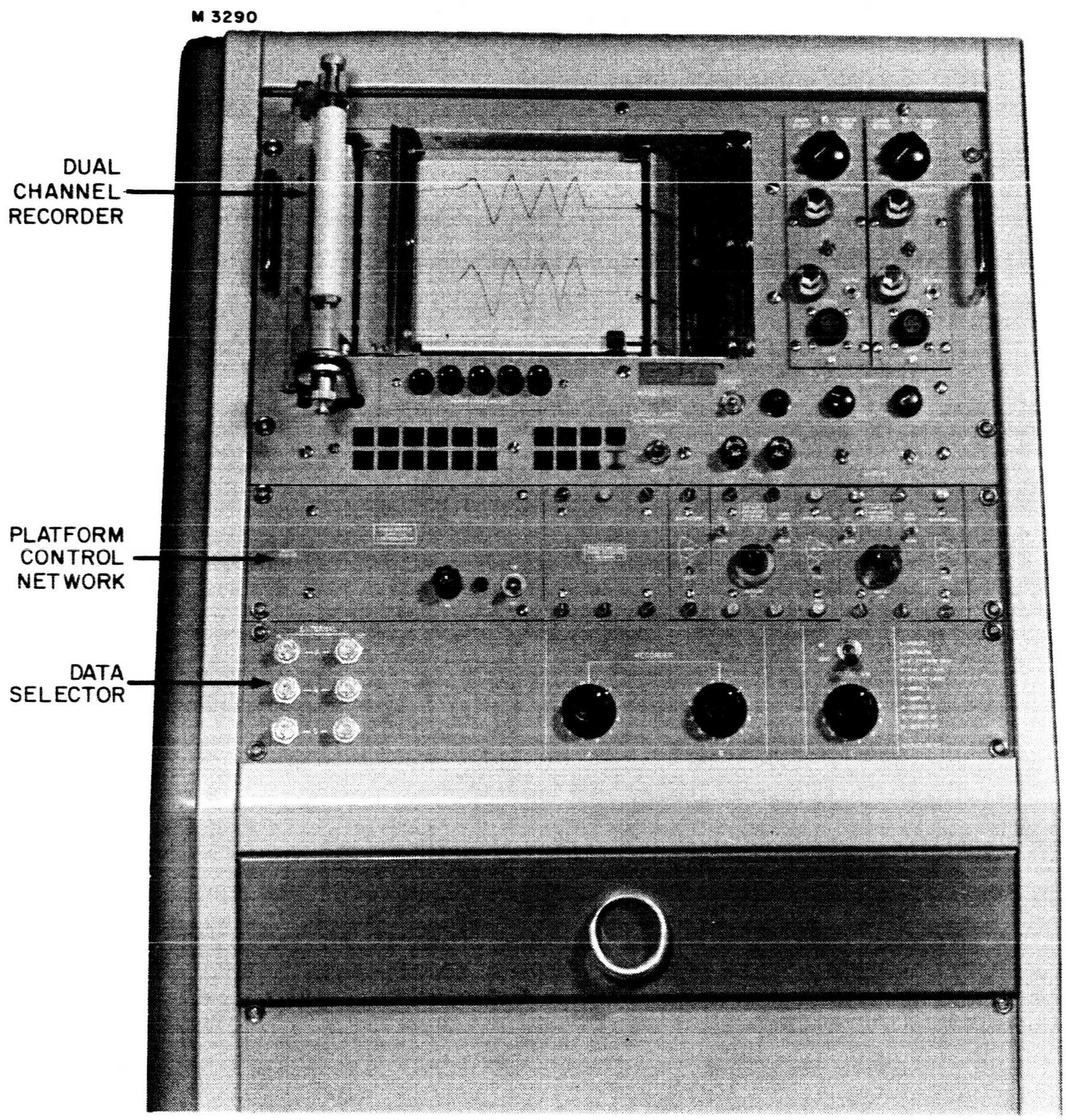

Fig. 18. Upper Left Panel.

C. Data Selector Panel

The Data Selector Panel shown in Fig. 18 comprises three rotary selector switches (A, B, C), six input/output coaxial connectors, and a digital voltmeter control switch. Selector switches A and B provide the inputs to channel A and B of the Sanborn Two Channel Recorder. Selector C provides the input to the Hewlett-Packard Digital Voltmeter through the panel telephone switch. Each selector provides the following outputs:

1. Thrust, lb
2. Impulse, lb-sec
3. Platform Displacement
4. Counter Weight Position
5. Static Load
6. Amplifier 1
7. Amplifier 2
8. Servo 1F
9. Servo 2F
10. Servo 3F
11. Spare
12. External Input

Positions 1 through 10 of selectors A, B, and C are connected in parallel. Position 11 is blank and provides a spare position for instrumentation. Position 12 is connected to external input coaxial connectors provided on the front panel.

The external output coaxial connectors (A, B, C) are connected to the wiper arm of each selector switch to provide for additional instrumentation. Channels A and B of the Sanborn Recorder are wired internally to Selectors A and B, respectively, with the Hewlett-Packard Digital Voltmeter (DVM) connected to Selector C through a telephone type function switch. When in the up position the function switch connects

Selector C directly to the DVM. In the center position, the DVM has a floating input. In the down position, the DVM input is grounded through a 15 K ohm resistor.

The following lists the data which may be displayed on the Sanborn Recorder and Digital Voltmeter or brought out to external instrumentation.

	Position	Description
1.	Thrust:	Instruments Thrust directly. 1,000 V is full scale of selected range, i.e., 0.01 Thrust/Impulse Scale — 1.000 V = 0.01000 lb; likewise 1.0 Thrust/Impulse Scale — 1.000 V = 1.000 lb. Instrumentation reads the output of a 0.1% resistance network.
2.	Impulse:	Instruments Impulse directly. 1.000 V is indicated scale of selected range. Output may be driven to 10 V without exceeding amplifier limitations, i.e., 0.01 Thrust/Impulse scale — 1,000 V = 0.01000 lb-sec; 9.999 V = 0.09999 lb-sec. Instrumentation reads the output of Impulse Integrator (Amplifier 3).
3.	Platform Displacement:	Thrust Platform Displacement. Instruments the output of the Sanborn Transducer Amplifier Indicator directly. Full scale sensitivity is 3.0 V dc, i.e.,

Scale	Displacement, μ in.	Output, V dc.
x1	15	3.00
x2	30	3.00
x5	75	3.00
x10	150	3.00
x20	300	3.00
x50	750	3.00
x100	1500	3.00
x200	3000	3.00

4. Balance Weight Position: Instruments the wiper arm of the Counter Weight Position Control potentiometer. Used to provide an accurate voltage reference setting for the counter-weight position servo motors.

5. Static Load: Static Load Adjustment. Instruments the wiper arm of the Static Load Adjust potentiometer. Used to provide an accurate voltage reference setting for the static force servo motor.

6. Amplifier 2: Instruments the output of Amplifier 1 — the Thrust Network Integrator. Used as a troubleshooting aid and for the setting of Thrust Initial Conditions.

7. Amplifier 2: Instruments the output of Amplifier 2 — the platform force motor driving amplifier. Used as a troubleshooting aid and for the monitoring of driving voltage to the force motor.

8. Servo 1F: Instruments the wiper arm of Counter Weight No. 1 servo followup potentiometer. . Indicates the counterweight vertical position. At steady state, voltage reading should match driving voltage of the Balance Weight Position potentiometer selector position 4.

9. Servo 2F: Instruments the wiper arm of Counter Weight No. 2 servo followup potentiometer. . Indicates the vertical position of the counter weight. At steady state voltage should match driving voltage of the Balance Weight Position potentiometer selector position 4.

10. Servo 3F: Instruments the wiper arm of counterweight No. 3 servo followup potentiometer. Indicates the counterweight vertical position. At steady state, voltage should match driving voltage of the Balance Weight Position potentiometer selector position 4.

11. Spare: No connection.

12. External Input: Instrument inputs from the External Input coaxial connectors.

D. Amplifier Balance

The Platform Control Network (PCN) comprises four solid state, chopper stabilized dc amplifiers. The chopper stabilization circuitry, incorporated in each amplifier unit, effectively reduces dc drift by chopping the dc signal, amplifying the chopped signal as ac, and demodulating to uncover the dc signal.

Three zero adjustments for the Thrust Integrator, Impulse Integrator, and Power Amplifiers are located on the front panel of the PCN. The differentiating circuit, located at the back of the PCN chassis, is not provided with a zero adjustment because of the nature of the circuit function.

With the inputs to the amplifiers grounded, each amplifier output is adjusted to a null by the following procedure:

1. Place the system in "Reset."
2. Turn "Off" the Sanborn Two Channel Recorder. Noise pickup from the Sanborn Recorder slightly affects the amplifier null.
3. Set the four (4)miniature toggle switches on the PCN to their normally down position.
4. Set the Digital Voltmeter telephone switch to the down position. Set the DVM to maximum sensitivity (100 mV range). Check the DVM zero and calibration (8000).
5. Place the DVM telephone switch to the up position and turn DVM selector to position 2. This position reads output of the Impulse Amplifier (Amplifier 3). Set the screwdriver adjustment No. 3 for a null on the DVM.
6. Turn the DVM selector to position 6 (Output Amplifier No. 1). Set screwdriver adjustment No. 1 for a null on the DVM.
7. Turn DVM selector to position 7 (Output Amplifier No. 2). Set screwdriver adjustment No. 2 for a null on the DVM.

The amplifiers are now balanced and ready for operation.

E. Transducer Amplifier Indicator Alignment

Platform displacement is instrumented by a linear variable differential transformer and carrier amplifier. This unit built by

Sanborn is discussed at length in the commercial manuals; however, a brief summary of adjustment procedures required by this application is justified.

The armature of the LVDT shown in Fig. 19 is mounted on the platform. This mounting location is shown circled in Fig. 3. The carrier amplifier with adjustments is located in the upper right quarter panel of the console. Two important considerations in the adjustment of the transducer are (1) electrical phase and amplitude adjustment and (2) alignment of the electrical and mechanical null.

The adjustment of the electrical balance is done as follows:

1. Place the system in "Standby." UNCAGE PLATFORM
2. Turn the Sensitivity control counterclockwise.
3. Turn the Attenuator selector to Mech Zero.
4. Turn the Detector knob to Bal.
5. Adjust the mechanical location of LVDT stator for a null on the meter.
6. Turn Attenuator to x200 or lower and adjust Res and Cap of the Transducer Balance for minimum. Continue adjustment of Res and Cap down to x1 attenuator scale.
7. Turn Detector to Use.
8. Turn Attenuator to x200 and adjust Position for zero on meter.
9. Turn Attenuator to x5 and adjust Res for zero. Repeat steps 7 and 8 as required to minimize meter movement as Attenuator scale is changed.
10. Lock final values on Res and Cap. No further adjustment of these controls will be necessary.

The alignment of the electrical and mechanical nulls can be accomplished as follows:

1. Place the system in "Reset."
2. Set the Thrust/Impulse Range switch for 5 lb.

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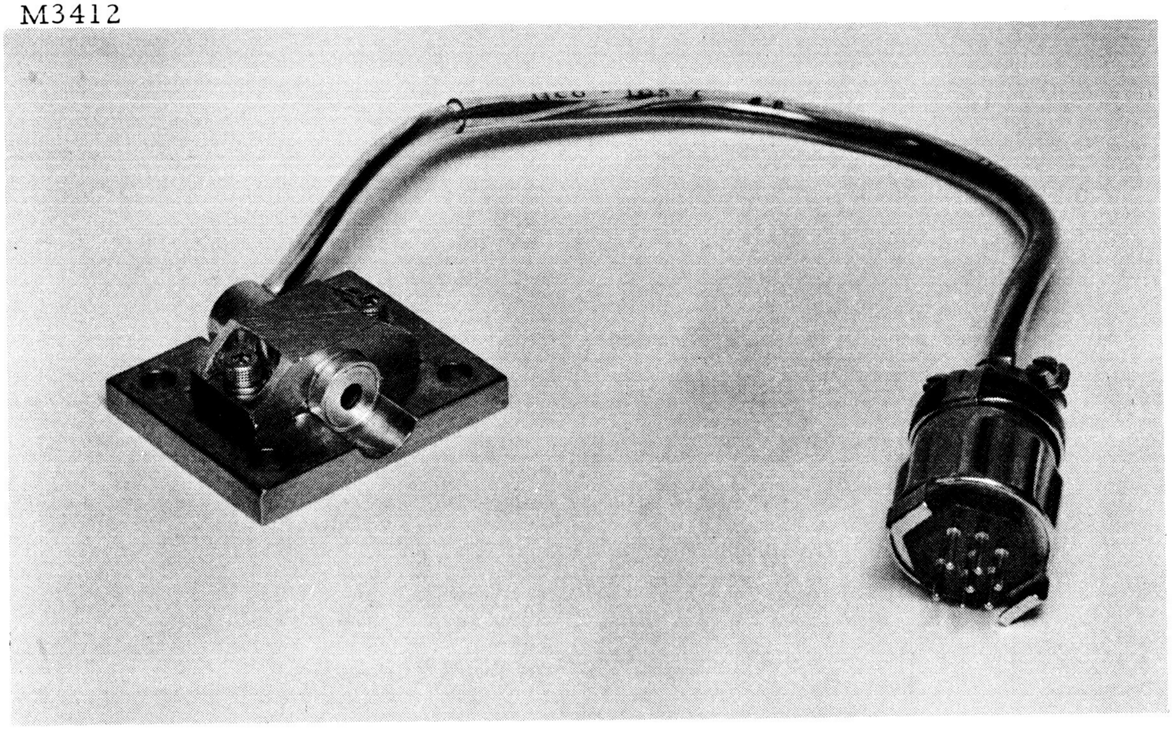

Fig. 19. LVDT.

3. Set Selector C (DVM Selector) to Thrust (position 1).
4. Turn DVM Scale to 10 V range.
5. Turn Transducer Attenuator to x100.
6. Place the system in "Operate."
7. Adjust stator of transducer for a zero of minimum on DVM.
8. Repeat above for lower T/I ranges. Increase system gain by using lower attenuator settings on the lower range.

The following final attenuator settings are recommended for optimum system operation.

Thrust/Impulse Range	Attenuator
5.0	x100
1.0	x50
0.1	x5
0.01	x1

The Sensitivity adjustment should be fully counterclockwise during normal use. Increased sensitivity is at the option of the operator; however, platform stability will limit the maximum loop gain. Excess gain will be noticed as a loud audible tone or as a high frequency vibration of the recorder pin on the Thrust or Displacement selector settings.

F. Thrust/Impulse Range Calibration

Calibration adjustments for the 0.01, 0.1, 1.0. and 5.0 Thrust/Impulse ranges are located within the Platform Control Network. For alignment and calibration of these four ranges, the subsequent procedure should be followed.

1. Place the system in the "Reset Mode" of operation.
2. Check the calibration of the Hewlett-Packard Digital Voltmeter (DVM). Set the DVM to the 10 V range.

3. Remove the four front panel mounting screws on the Platform Control Network and slide the complete chassis forward approximately 4 in. Set a small block on the top of the unit to keep it from sliding back into the console.
4. A visual inspection of the top of the Platform Control Network Chassis will reveal seven calibration trim pots (R_1, R_2, R_3, R_4, R_5, R_6, R_7).
5. Set Selector C to Position 1 (Thrust). Set the Digital Voltmeter function switch to the "up" position.
6. With the system in "Reset" select the 5.0 lb Thrust/Impulse Range.
7. Set the system to the "Static Calibrate" mode of operation.
8. Null the Digital Voltmeter with the Position Control located on the Transducer Amplifier Indicator. This provides a limited electrical trim adjustment of the platform balance. If a null cannot be attained, repeat the transducer calibration procedure.
9. Insert the 1 lb calibration capsule into the Static Force Unit located at the front of the thrust stand.
10. With the 1 lb capsule calibration curves and the Static Load Adjust, located on the console front panel, set the static force to 1 lb and record the potentiometer setting for futrue reference.
11. Because of the small fractional horsepower motor driving the static force load, the time lag to steady state (for 0 to 1 lb) will be approximately 1 min. A red lamp "On" condition of the Static Calibrate servo drive indicator lamp indicates that the static force has not reached its steady state position. The red lamp will extinguish when the force unit has driven to the position corresponding to the helipot setting.

12. When the Static Cal servo drive lamp has extinguished, place the system into the "Operate Mode." The computer loop will now generate a driving current to the restoring force motor of a magnitude to balance the platform at the mechanical null.

13. Adjust R_7 for 0.100 V on the Digital Voltmeter. This adjustment allows direct reading of the 1.000 lb force.

14. Set the system to "Static Calibrate" and set the Static Load Adjust potentiometer to zero. When the red drive lamp has extinguished, place the system into "Reset" and select the 1.0 lb Thrust/Impulse Range.

15. Set the system to "Static Calibrate." Repeat step 8.

16. Reset the Static Load Adjust to 1.0 lb. When the red drive lamp has extinguished, place the system into "Operate."

17. Adjust R_4 for 1.000 V on the digital voltmeter. This sets the 1.0 lb range.

18. Turn Selector C to position 7 (Amplifier 2). Adjust R_6 for 10.00 V on the digital voltmeter. This sets the upper voltage limit on the power amplifier stage.

19. Place the system in the "Static Calibrate" mode and set the Static Load Adjust potentiometer to zero. When the red drive lamp has extinguished, insert the 0.1 lb calibration capsule into the Static Force Unit.

20. Place the system in "Reset" and select the 0.1 lb Thrust/Impulse Range.

21. Return the system to the "Static Calibrate" mode and set in a 0.1 lb static force by the aforementioned procedure. Record the potentiometer setting.

22. When the red drive lamp has extinguished, place the system in "Operate." Turn Selector C to Position 1 (Thrust).

23. Adjust R_3 for 1.000 V on the digital voltmeter.
24. Turn Selector C to Position 7 (Amplifier 2) and adjust R_5 for 10.00 V.
25. Set the system to Static Calibrate. Set the Static Load potentiometer to zero. Wait for the red lamp to extinguish.
26. Place the system in "Reset." Select the 0.01 lb T/I Range. Place the system back into Static Calibrate.
27. Repeat Step 8.
28. Set the Static Load Adjust for 0.01 lb. When steady state is reached, place the system into "Operate."
29. Set Selector C to Position 1 (Thrust) and adjust R_2 for 1.000 V.
30. Turn Selector C to Position 7 (Amplifier 2) and adjust R_1 for 10.00 V.
31. The Thrust/Impulse Ranges are now calibrated. Return the system to "Static Calibrate" and set the Static Load Adjust to 0.050. When steady state is reached, the Static Force motor button should, by visual inspection, be just free of contact with the stand.
32. The system is now ready for operation.

Calibration	Thrust/Impulse Range	Power Amplifier 2 Range
"Selector C" Range	Position 1 Adjustment	Position 7 Adjustment
5 lb	R_7 to 1.000 V	
1 lb	R_4 to 1.000 V	R_6 to 10.00 V
0.1 lb	R_3 to 1.000 V	R_5 to 10.00 V
0.01 lb	R_2 to 1.000 V	R_1 to 10.00 V

G. Static Calibrate

Static calibration of the platform restoring force is provided by a precision servo driven coil spring located in the Static Calibrate Unit, Fig. 20. Three spring capsules -1, -2, -3 have been provided for static load calibration up to 5 lb. The range covered by each capsule is as follows:

Drawing No.	Range, lb
836027-1	0.01 - 0.1
836027-2	0.1 - 1.0
836027-3	0.5 - 5.0

The appropriate calibration capsule may be easily inserted in the servo drive assembly by removing the static force unit cover plate. Proper operation requires only finger tight installation of the capsule.

Figures 21 and 22 of position potentiometer dial reading and force have been prepared for capsules -2 and -3.

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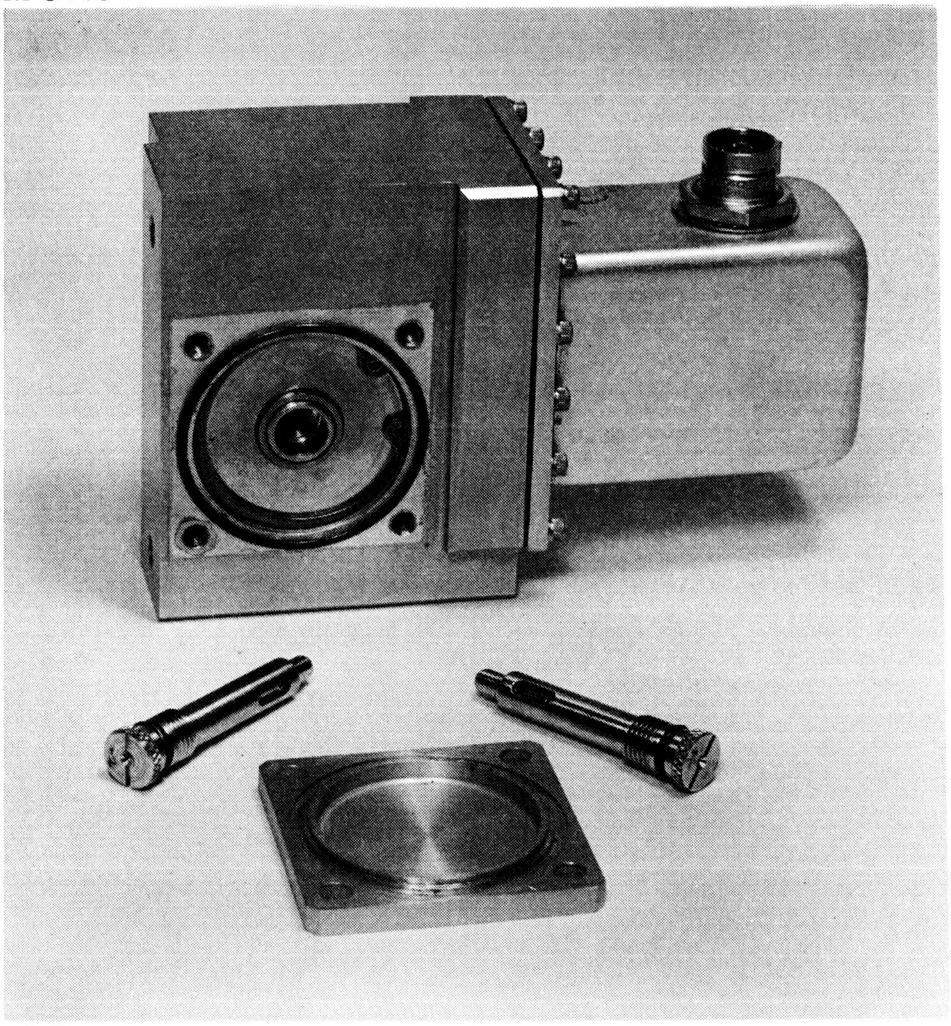

Fig 20 . Static calibrator head.

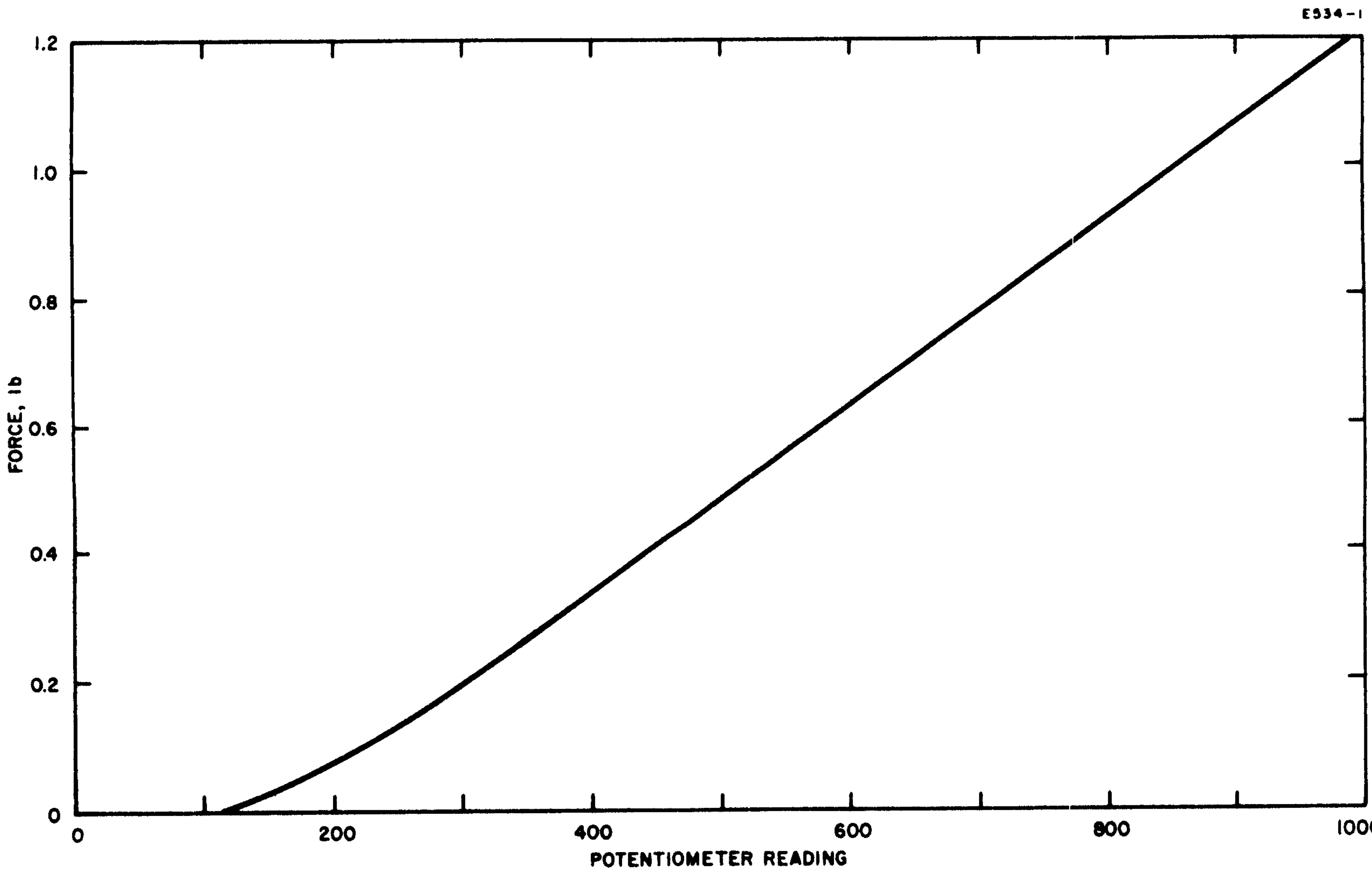

Fig. 21. Graph of position potentiometer dial reading and force.

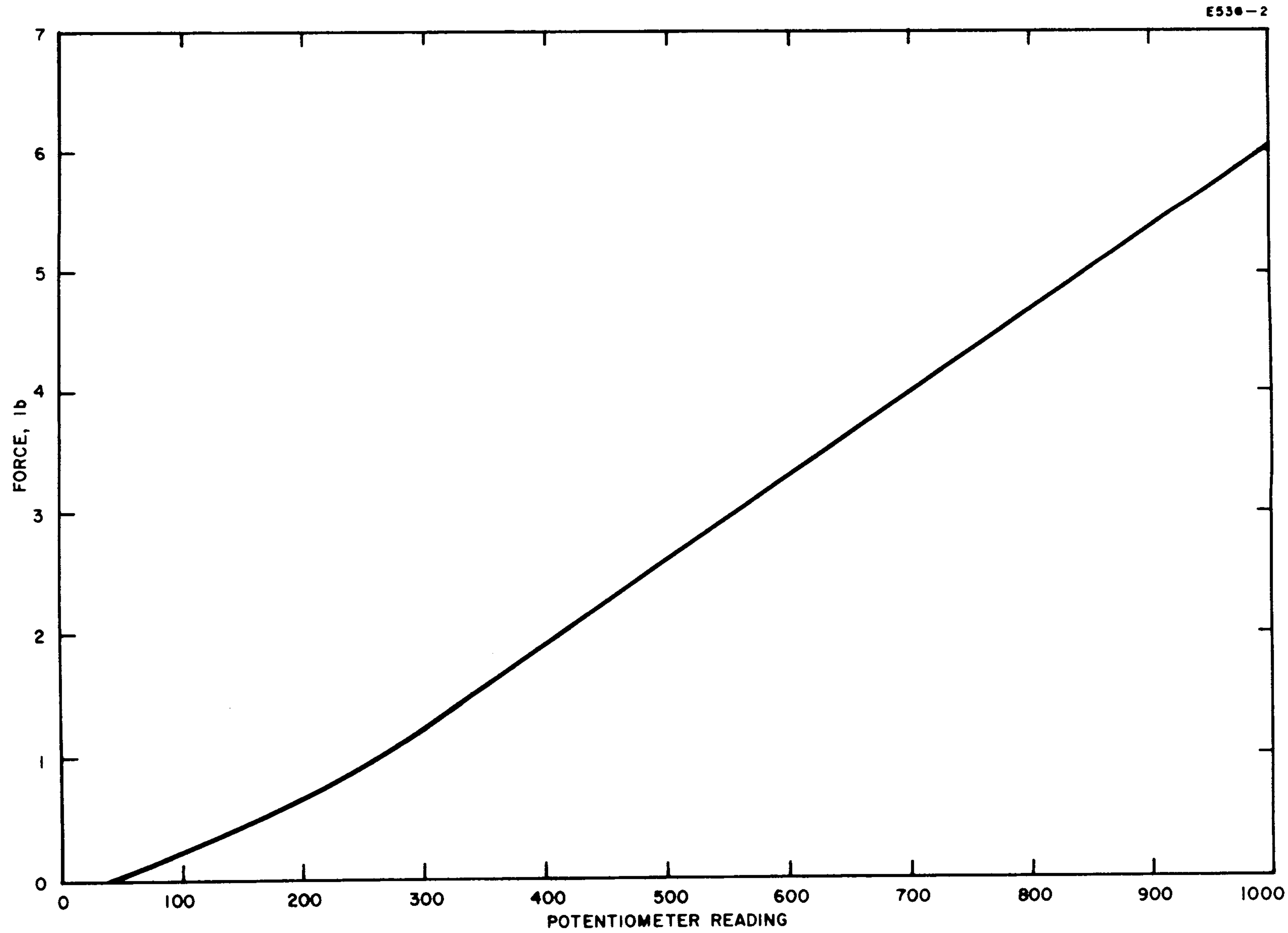

Fig. 22. Graph of position potentiometer dial reading and force for capsule-3.

VI. DRAWINGS AND SCHEMATICS

Complete Mechanical and Assembly drawings of the thrust stand system have been provided to LeRC and are not included in this manual.

Electrical schematics and wiring lists are enclosed with this manual, in unbound form. The following items are also included:

Number	Title
23	Thrust stand system console layout drawing
24	Outline drawing of thrust stand mounted in vacuum chamber
25	Indicator Panel
26	Mode Selector
27	Data Selector
28	Platform Control Network
29	Transducer, Amplifier/Indicator
30	Servo Amplifier (top view)
31	Servo Amplifier (bottom view)
32	Servo Amplifier (rear view)
33	Voltage Regulator

Instruction manuals on purchased electronic equipment have been provided to LeRC, and should be available to maintenance and repair personnel.

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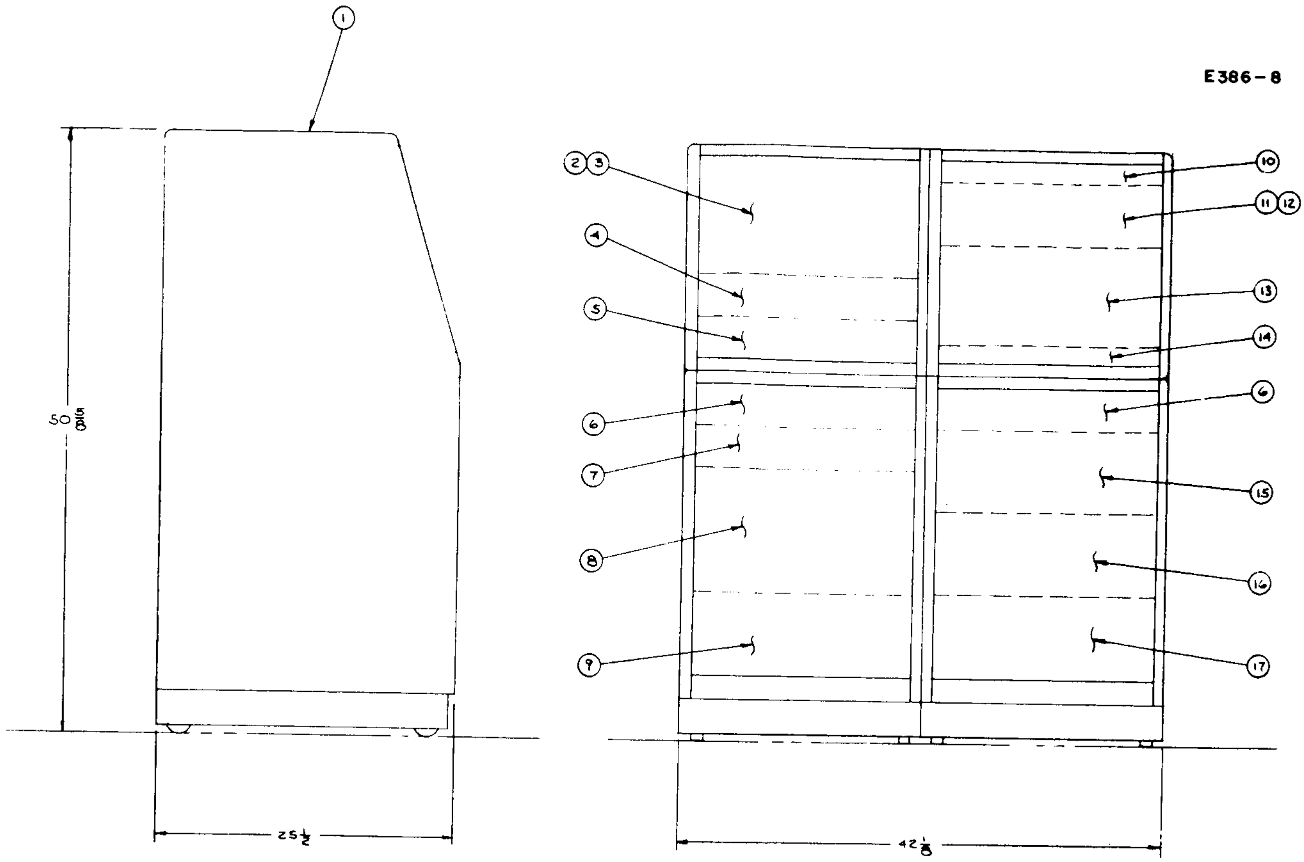

NO. REQ'D	PART NO.	DESCRIPTION	ITEM NO.
			20
			19
			18
1[c]	DRA-7B-23	Drawer	17
1	835739	Assy-Power Supply	16
1	835738	Assy-Servo Amplifiers	15
1	835736	Assy-Console Operational Control	14
1[a]	835745	Assy-Transducer Indicator and Null Voltmeter	13
1[a]	3443-A	Range Selector	12
1	3440-A	Digital Voltmeter	11
1	835733	Assy-Status Indicator	10
1[d]	B-27	Blower	9
1	835744	Assy-Constant Voltage Regulator	8
1	835734	Blank Panel	7
2[c]	RS-22A	Retractable Shelves	6
1	835737	Assy-Calibration Selectors	5
1	835735	Assy-Operational Amplifier and Power Supply	4
2[b]	850-1300B	D. C. Coupling Preamplifiers	3
1[b]	297	Dual Channel Recorder	2
1	835730	Assy-Rack	1

[a]Hewlett Packard Co., Loveland, Colorado
[b]Sanborn Co., Waltham, Mass.
[c]Ingersol Products, Div.of Borg-Warner Corp., Chicago, Illinois
[d]Bud Metal Products, Cleveland, Ohio

Fig. 23. Thrust stand system console layout drawing.

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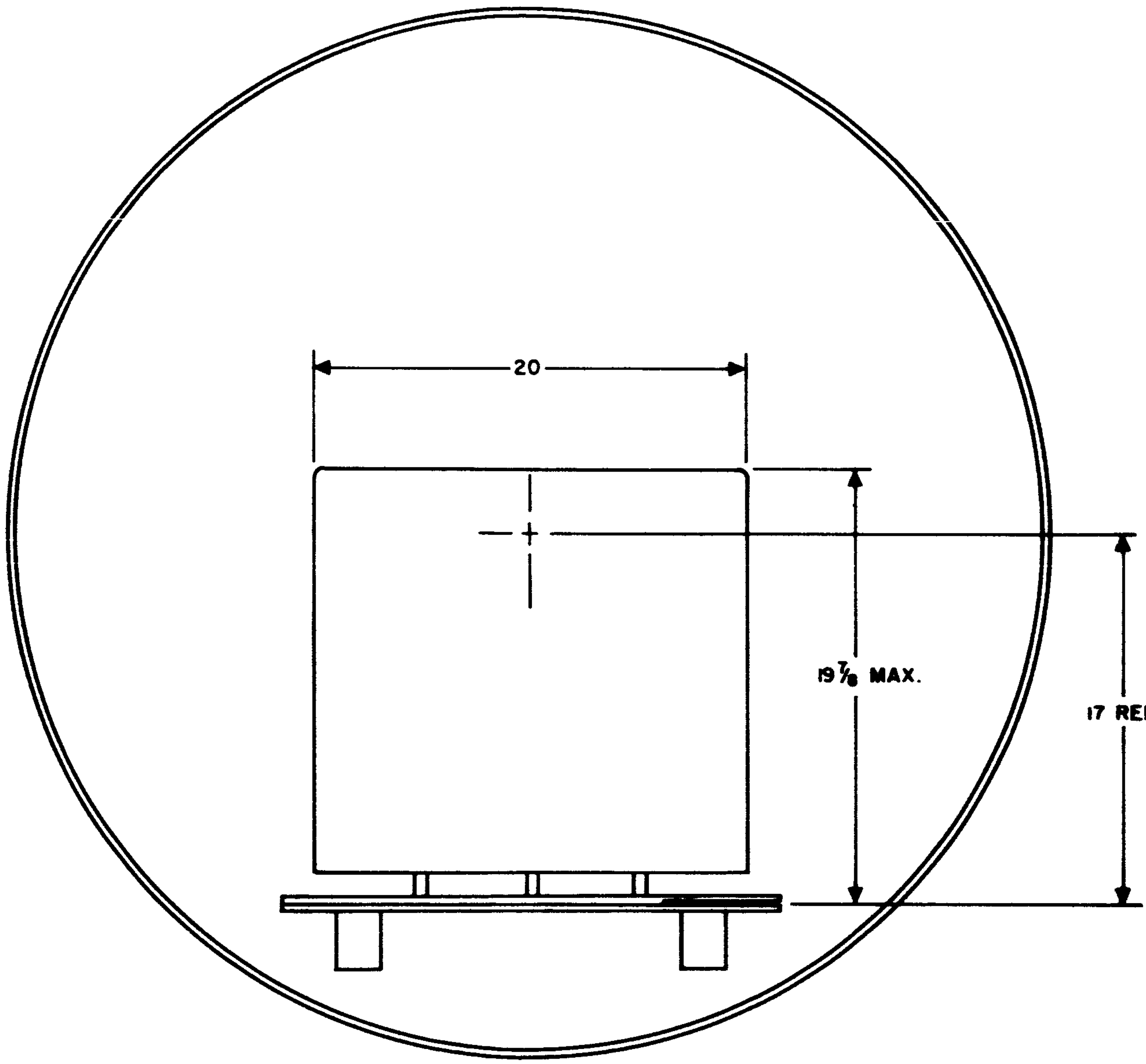

Fig. 24. Outline drawing of thrust stand mounted in vacuum chamber.

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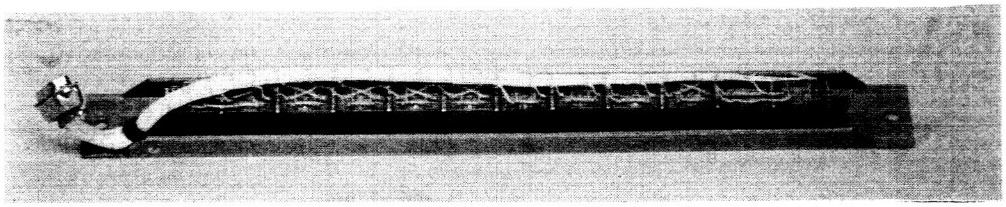

Fig 25. Indicator Panel.

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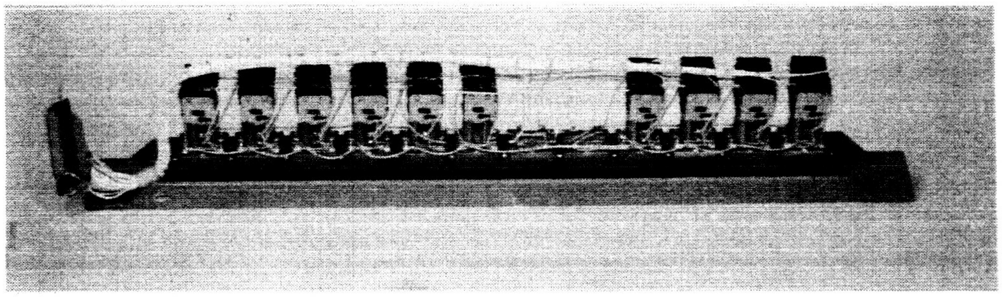

Fig. 26. Mode Selector.

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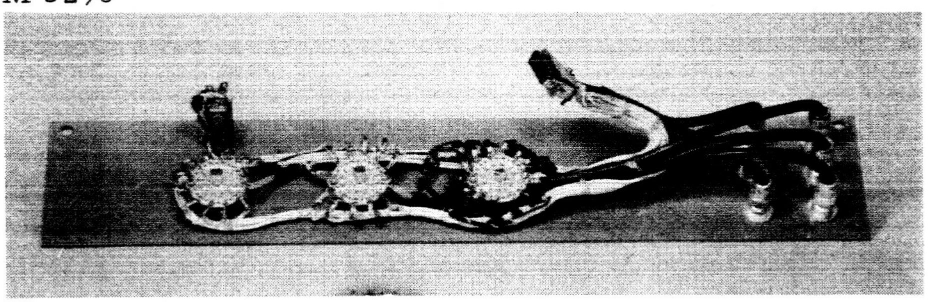

Fig 27. Data Selector.

M 3298

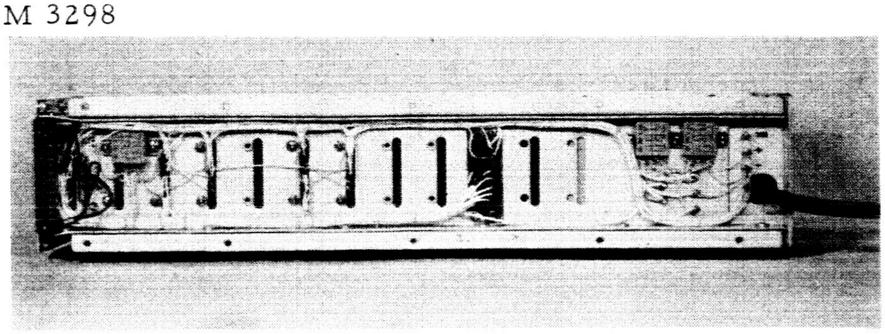

Fig. 28. Platform Control Network.

M 3295

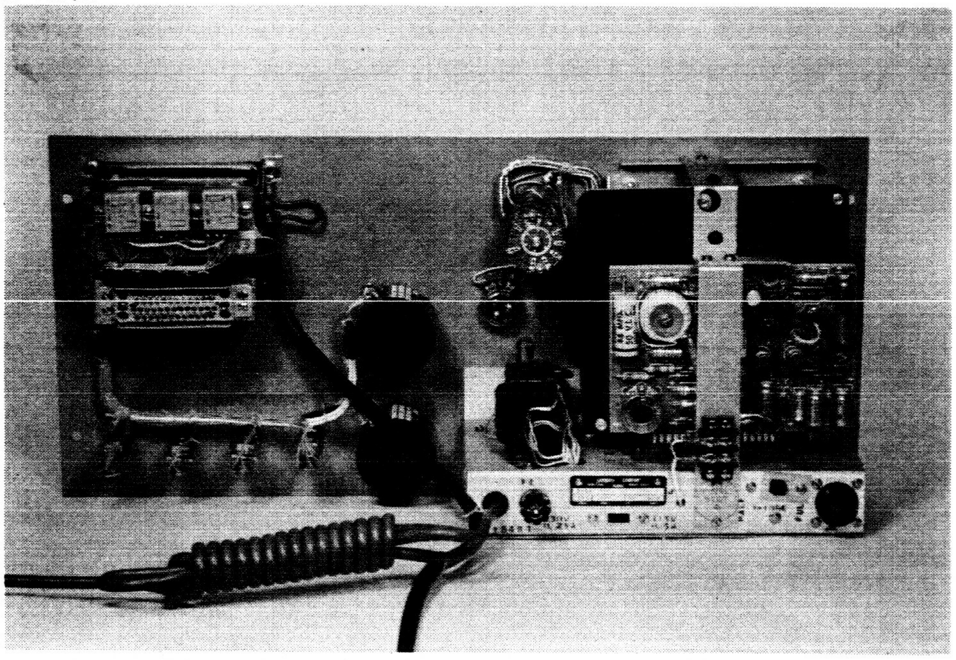

Fig. 29. Transducer, Amplifier/Indicator.

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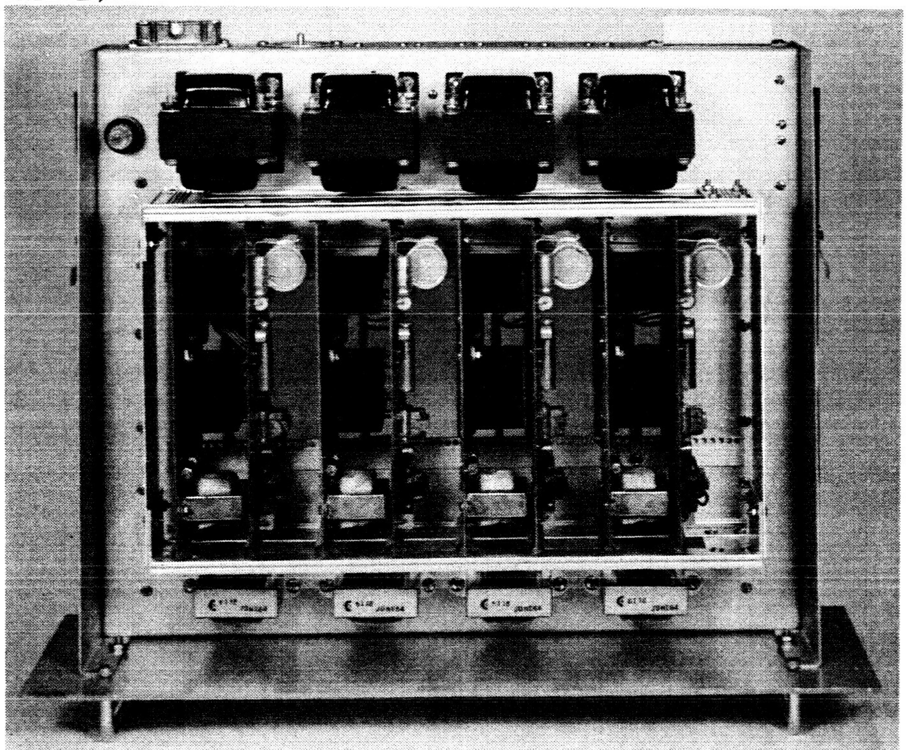

Fig 30 Servo Amplifier (Top View).

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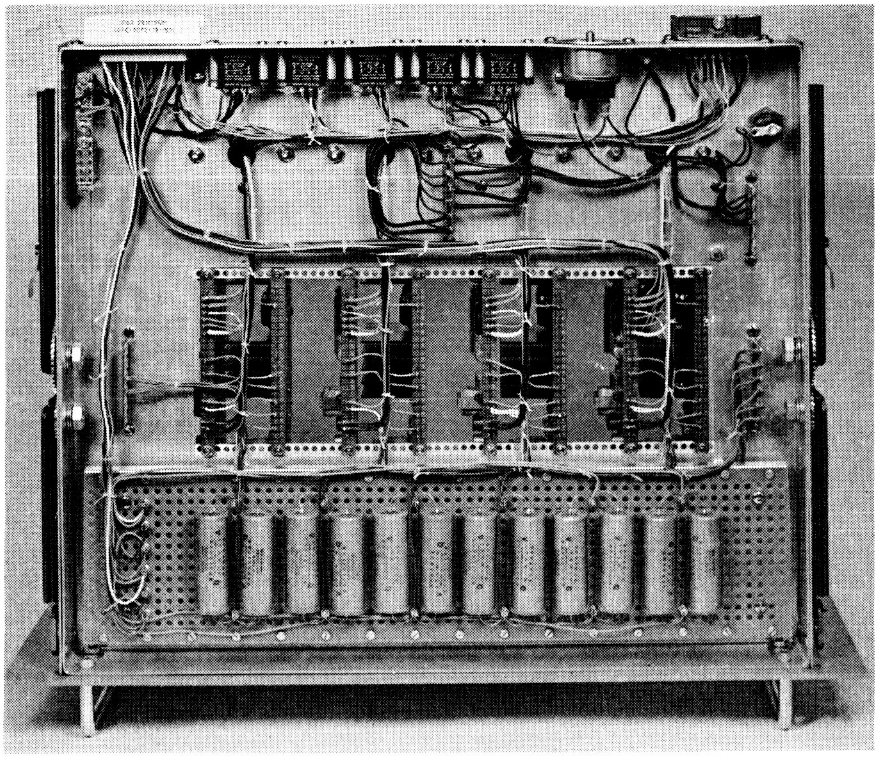

Fig. 31. Servo Amplifier (Bottom View).

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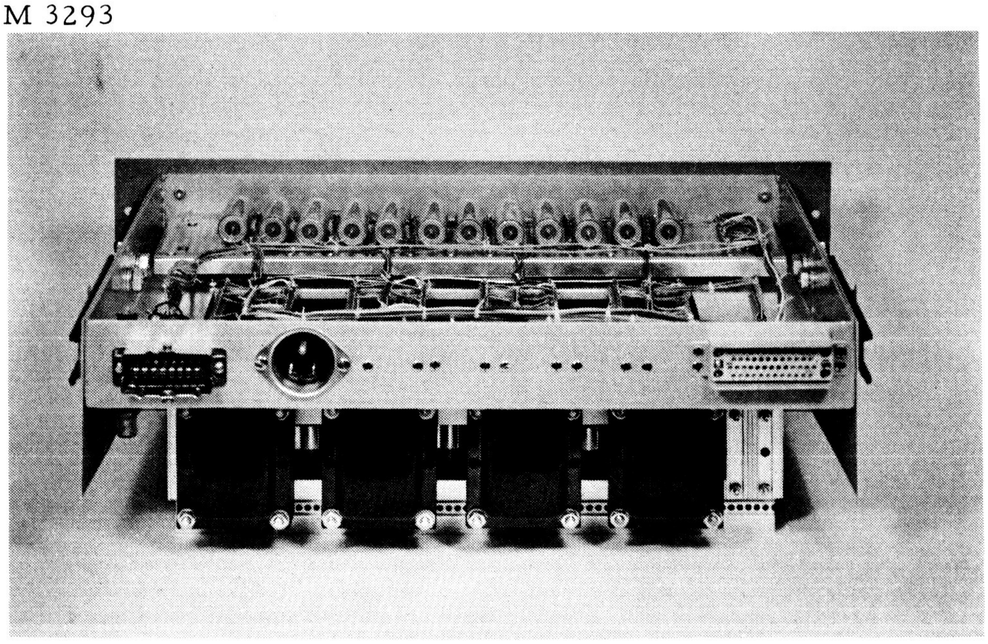

Fig. 32. Servo Amplifier (Rear View).

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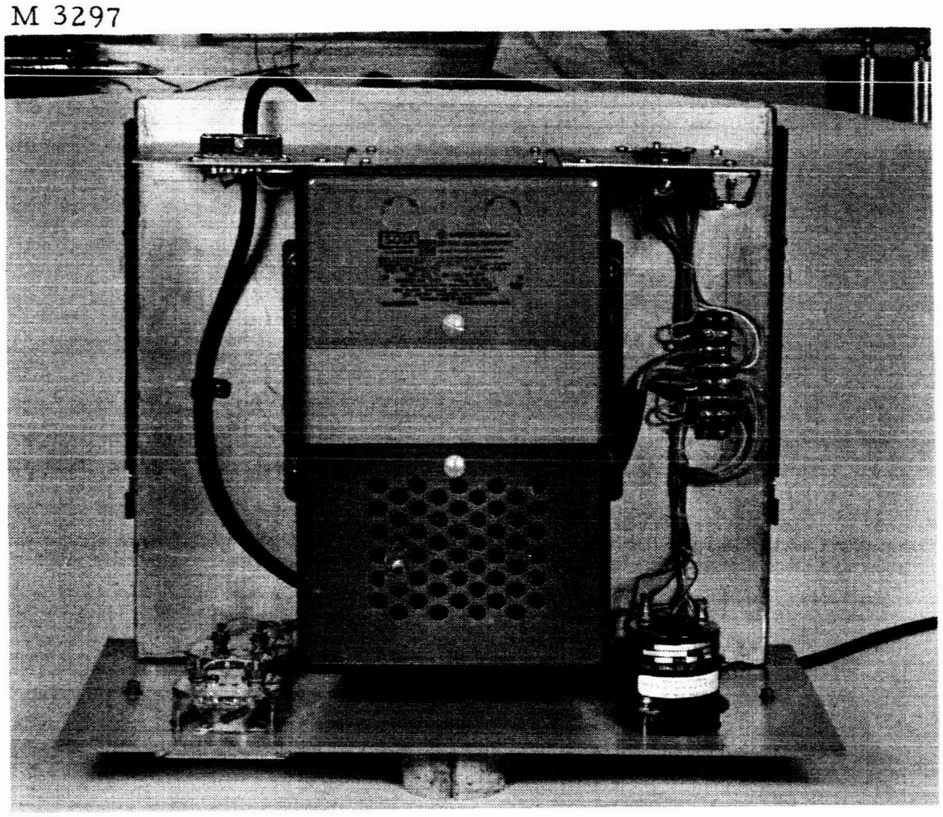

Fig. 33. Voltage Regulator.